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**CHROMATOGRAPHIC
CHARACTERISTICS
AND PHYLOGENETIC
RELATIONSHIPS OF
ARTEMISIA,
SECTION TRIDENTATAE**

**David L. Hanks,
E. Durant McArthur, Richard Stevens,
and A. Perry Plummer**



**INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Ogden, Utah 84401**

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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Robert W. Harris, Director

THE AUTHORS

DAVID L. HANKS was a Plant Physiologist in 1969 and 1972 for the Intermountain Forest and Range Experiment Station in Ephraim, Utah. He received his B.S. degree in Botany (1962) and M.S. degree in Chemistry (1963) from Brigham Young University. He obtained his Ph.D. in Plant Physiology (1966) from the University of Michigan. Between 1966 and 1969, he taught mycology and plant physiology at Brigham Young University. He is presently Assistant Professor of Microbiology, Division of Science, at Northeast Missouri State University, Kirksville, Missouri.

E. DURANT McARTHUR is a Research Geneticist for the Intermountain Station at Ephraim. His degrees are from the University of Utah: B.S. in Genetics and Cytology (1965), M.S. in Molecular and Genetic Biology (1967), and Ph.D. in Biology (1970). He was a Postdoctoral Research Fellow of Agricultural Botany at the University of Leeds, United Kingdom, in 1970-1971. He joined the Station in 1972.

RICHARD STEVENS is a Game Biologist for the Utah Division of Wildlife Resources. He received his B.S. degree in Range Management (1965) from Brigham Young University, and his M.S. degree in Range Management (1968) from the University of Arizona. From 1968 to 1969 he was a Range Conservationist with the USDA Forest Service. He has been in his present position since 1969.

A. PERRY PLUMMER is a Range Scientist for the Intermountain Station at Ephraim. He has worked in range research for the Station since 1936. He received his B.S. degree (1935) and his M.S. degree (1939) in Botany from the University of Utah. His research has been principally concerned with the restoration of western ranges.

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ABSTRACT

On the basis of a chromatographic analysis, Artemisia tridentata is divided into seven subgroups; three of subspecies vaseyana, three of subspecies tridentata, and one of subspecies wyomingensis. The three subgroups included in A. tridentata subsp. tridentata show low utilization by game and livestock; the four subgroups included in subspecies vaseyana and wyomingensis show high utilization, especially on winter ranges. Although each subgroup occupies a distinctive ecological habitat, few consistent morphological differences are manifested, particularly among the subgroups of subspecies vaseyana and subspecies tridentata.

Chromatographic comparison of the species in the section Tridentatae suggests that subgroup IIc of A. tridentata subsp. tridentata may have been the ancestral form to develop from A. biglovii. In turn, this form probably gave rise to the remaining subgroups of A. tridentata and most other species in this section.

INTRODUCTION

The genus *Artemisia* section *Tridentatae*¹ occur discontinuously in plants on over one-third of that portion of the contiguous N. longitude (Beetle 1960). Some of these taxa also occur in the United States and in Canada and Mexico. Sagebrush is an important component of the rangeland. It serves as forage for wildlife and livestock and small animals. Moreover, sagebrush has watershed and

is noted for both intraspecific and interspecific morphological variability (Ward 1923; Ward 1953; Beetle 1960, 1970). Hybridization and polyploidization contribute to the morphological plasticity of the group. These factors have been important in the reticulate evolutionary past of the group. The variability of the group, Beetle's (Beetle 1960; Beetle and Young 1965) approaches practical workability.

The group was initiated by Diettert (1938). Diettert's and subsequent studies have led to the conclusion that the group is a polyploid series based on the chromosome number of 40; Ward 1953; Taylor and others 1964; Winward 1970). The group includes diploid ($n = 18$), hexaploid ($n = 27$), and octoploid ($n = 36$) populations. Although chromosome numbers for over 50 populations have been determined, meiotic or karyotypic studies have been performed. The results do not clarify the phylogenetic relationships within the group. However, in areas of the Northwest, diploids appear to be clearly separated by elevation (Ward 1953;

Tridentatae Rydb. is recognized over the analogous section *Semiphiidium* Besser. Taxonomic treatment of species follows Beetle (1960) and Beetle and Young (1965).



Figure 1.--Differential grazing of two *A. tridentata* subsp. *vaseyana* bushes in the Seeley Creek Drainage, Sanpete County, Utah.

Chemotaxonomic methods have recently been used to study taxa within the *Tridentatae*. Chromatographic investigations by Holbo and Mozingo (1965), Young (1965), Winward and Tisdale (1969), Hanks and others (1971), and Brunner (1972) give support to the taxonomic treatment of species and subspecies by Hall and Clements (1923) and Beetle (Beetle 1960; Beetle and Young 1965). Identification and distribution of leaf phenols, sesquiterpene lactones, and alkanes are proving to be of value in delimitating *Artemisia* species (Shafizadeh and Melnikoff 1970; Shafizadeh and others 1971; Bachelor and others 1972).

Our special interest in sagebrush arose primarily from questions as to why game and livestock exhibited marked preferences for certain big sagebrush populations (Brunner 1972) or for certain individuals in a population (fig. 1). In earlier chromatographic work (Hanks and others 1971; Hanks and Jorgensen 1973), we reported evidence for and means of detecting some of these differences in subspecies of big sagebrush (*Artemisia tridentata* subsp. *tridentata* and *A. tridentata* subsp. *vaseyana*). In the course of this research, chromatographic analyses were done on other species in the *Tridentatae* as well. This paper stresses some considerable differences discovered among these species through chromatographic studies in 1969 and 1972, and outlines phylogenetic relationships among these species as suggested by chromatographic patterns. Other chromatographic analyses have been performed in the *Tridentatae*; however, this study is much broader in scope and builds on earlier work.

The large amount of genetic variation in natural populations of *Artemisia* provides wide opportunity for the development of improved races through artificial selection and breeding. Chromatography offers a rapid means of verifying the existence and extent of hybridization and also a technique for identifying types that would satisfy specific purposes.

EXPERIMENTAL PROCEDURES

Chromatographic analyses of more than 350 plant specimens are included in this study. The plants chromatographed came from widely occurring populations in Utah, Idaho, Nevada, Wyoming, Colorado, Arizona, Oregon, and British Columbia, and include most species of the section *Tridentatae*. Attempts were made to collect from a wide variety of sites so that collections would be fairly representative of the distribution of species and subspecies. Although the majority of collections were taken from sites within the Great Basin, many were obtained from populations outside this geographical area.

Artemisia populations were sampled by collecting foliage from mature representative individual bushes. Naturally occurring and transplanted bushes were sampled. Transplanting apparently did not affect the chromatographic patterns. Sampled foliage consisted of persistent, overwintering leaves from nonflowering stalks. Leaves on *Artemisia* flowering stalks have been reported to give variable results in chromatographic studies (Winward and Tisdale 1969; Brunner 1972). Early results indicated little seasonal variation in chromatographic patterns from persistent leaves; consequently, foliage was collected during all seasons of the year. Foliage was placed in open brown paper bags and dried at room temperature.

A modification of the chromatographic methods developed by Alston and Turner (1962) was employed. A mortar and pestle were used to pulverize 0.5 g. of dried leaves. Samples were placed in 30 ml. bottles into which 7.0 ml. absolute methanol had been introduced. Extraction of phenolic substances was carried out at room temperature for 24 hours. The extract then was decanted and concentrated by evaporation to 2.0 ml.

Twenty-five μ l of this extract were added to duplicate 9-inch squares of Whatman No. 3 MM chromatographic grade filter paper. The solvent system for the first dimension was n-butanol:acetone:water (4:1:3) and for the second dimension, acetic acid:water (15:85). Chromatograms were viewed under longwave ultraviolet light before and after exposure to ammonia fumes in order to note the appearance and color changes of resulting spots. Each spot was given an arbitrary number for identification purposes and the R_f value computed for both dimensions of the finished chromatogram.

$$R_f = \frac{\text{Distance of spot from starting point}}{\text{Distance of solvent front from starting point}}$$

The R_f value of a given spot is then expressed as:

$$R_f = R_f(\text{first dimension})/R_f(\text{second dimension}).$$

Thin-layer plates coated with silica gel G were photographed to illustrate the difference among groups of big sagebrush. Each plate was divided into three 6- by 20-cm. sections and the base of each section was streaked with approximately 200 μ l of extract. Chromatograms were developed in a single direction using n-butanol:acetone:water (4:1:1) as the solvent system. Following development, the plates were exposed to ammonia fumes, allowed to dry, and photographed under ultraviolet light (Kodachrome II film, ASA 25, and a 2B filter).

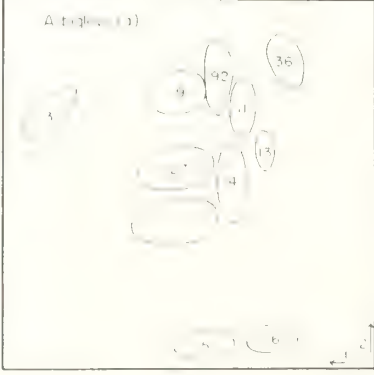
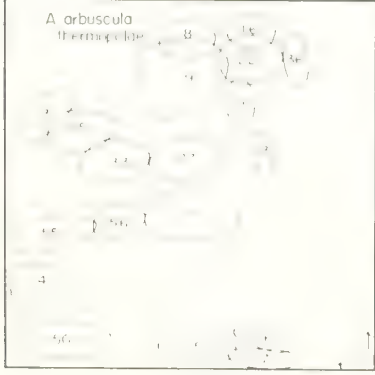
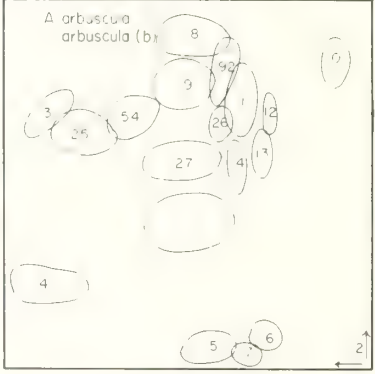
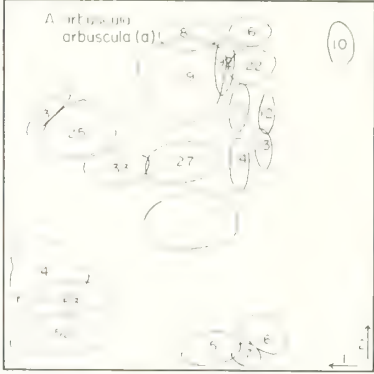
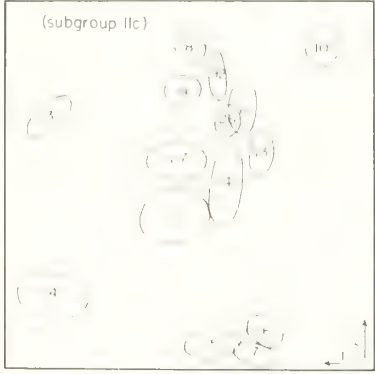
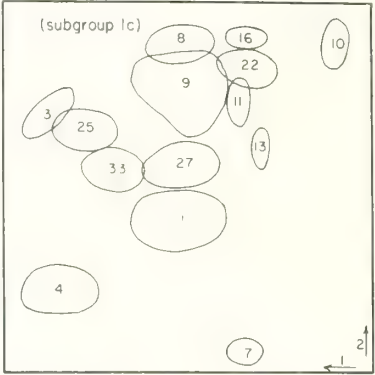
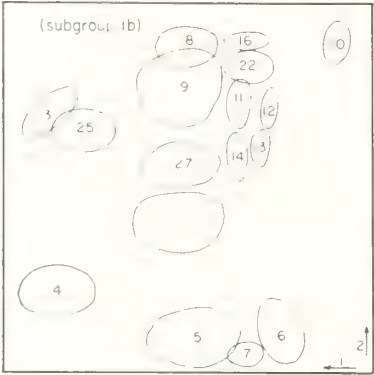
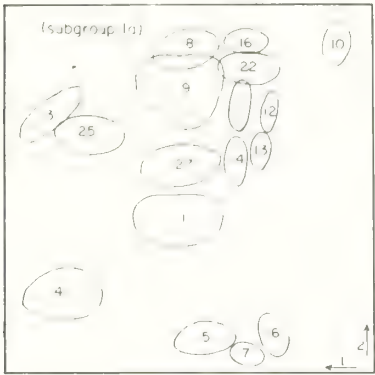
Identification of the constituents of the methanol extracts is beyond the scope of this paper. Shafizadeh and Melnikoff (1970) report that phenolic extractives of *Artemisia tridentata* subsp. *vaseyana* leaves are mainly coumarins with various side chain substituents.

RESULTS

On the basis of chromatographic variations among collections of big sagebrush, the sources studied are divided into two major groups and seven subgroups (figs. 2-8 and table 1). Several of the chromatographic spots exhibited significant variations in size and intensity of color; so both qualitative and quantitative (table 2) variations were taken into consideration when the chromatograms were organized into groups. Characterization of chromatographic spots of big sagebrush by R_f values and colors (figs. 2-8 and table 2) is nearly identical with data presented in an earlier paper (Hanks and others 1971). The few changes represent judgments reached after further investigation, except for the R_f value of spot 4, which was misprinted in Hanks and others (1971). The missing numbers in the sequence (table 2) represent spots that appeared only occasionally in the chromatograms and, in most instances, provided no useful basis for the organization of the collections into groups. However, some of these might be indicative of past hybridization between big sagebrush and other sagebrush species.

Variation within species or subspecies was also observed among other species. Representative chromatograms of each (i.e., *A. arbuscula* subsp. *arbuscula*, *A. arbuscula* subsp. *triaristata*, *A. tridentata*, *A. canescens* subsp. *canescens*, *A. canescens* subsp. *tridentata*, *A. elaeagnifolia*, *A. elaeagnifolia* subsp. *elaeagnifolia*, *A. elaeagnifolia* subsp. *rockii*, *A. tripartita* subsp. *tripartita*) are illustrated in figures 9-25. Distribution of chromatographic spots among each is included in table 1. R_f values and color variations of the individual spots are given in table 2.

Figures 2-25.--Representative two-dimensional chromatograms of methanol-soluble extracts from the leaves of the subgroups of *A. tridentata* (figs. 2-8) and other species of section *Tridentatae* (figs. 9-25). For spot coloration and R_f values, see table 2.



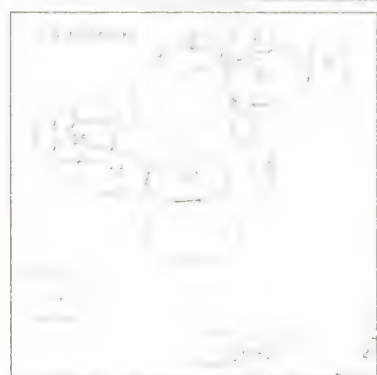
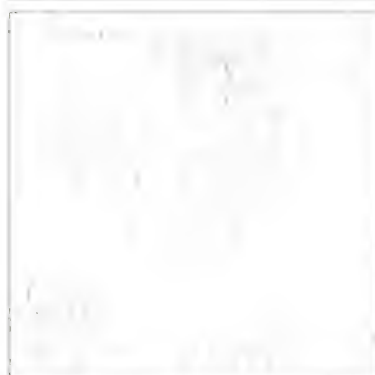
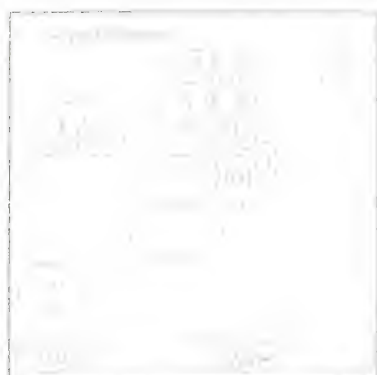


Table 2.--*Thin layer chromatography of the volatile fraction of Artemisia tridentata*

Spot no.	R _f	Color		
		Ultraviolet	NH ₃ + ultraviolet	NH ₃ + daylight
1	0.53/.46	Blue	Yellow-green	Gray
3	.88/.71	Blue-green	Blue-green	--
4	.87/.29	Violet	Violet-brown	Yellow
5	.47/.11	Yellow or yellowish-brown	Yellow or yellowish brown	--
6	.28/.13	Yellow or yellowish-brown	Yellow or yellowish-brown	--
7	.32/.08	Violet	Violet	Yellow-brown
8	.51/.87	Dark blue	Dark blue	--
9	.54/.78	Bright, iridescent blue	Bright, iridescent blue	--
10	.18/.84	--	Blue	--
11	.34/.75	Blue	Yellow-green	Yellow
12	.26/.71	--	Blue-violet	--
13	.29/.64	Pink	Yellow-pink	--
14	.35/.59	Blue (Violet in Hc)	Gray-blue (Violet in Hc)	-
16	.32/.90	Dark blue	Dark blue	--
19	.50/.83	--	Orange	--
20	.80/.73	--	Orange	--
22	.32/.84	Blue	Blue-green	--
25	.83/.67	Blue-green	Blue-green	-
26	.38/.73	Blue	Blue	-
27	.51/.57	Blue	Yellow-green	Gray
33	.75/.60	Pinkish-white	Pink	--
36	.26/.84	Blue	Blue	-
50	.78/.07	Brownish-gold	Brownish-gold	-
51	.85/.79	--	Yellow-green	--
52	.85/.12	Brownish-violet	Brownish-violet	--
53	.85/.19	Brownish-violet	Brownish-violet	--
54	.67/.76	--	Blue-green	--
55	.87/.41	Violet	Blue-violet	--
56	.71/.42	--	Tan	-
57	.57/.53	Violet	Violet	--
92	.42/.82	Blue	Blue-green	--

Table 3.--Color of extract from each of seven subgroups of
A. tridentata under ultraviolet light

Subgroup	Color of extract under ultraviolet light
<i>vaseyana</i> Ia	Bluish-white to light blue
<i>vaseyana</i> Ib	Bluish-green to bluish-violet
<i>vaseyana</i> Ic	Creamy-white to bluish-white
<i>wyomingensis</i> Id	Brownish-violet to greenish-violet
<i>tridentata</i> IIa	Bluish-violet to greenish-violet
<i>tridentata</i> IIb	Greenish-violet
<i>tridentata</i> IIc	Violet to reddish-violet

Comparisons of single-dimension, thin-layer chromatograms of the seven subgroups of *A. tridentata* are shown in figures 26-32.

Another rapid, but less accurate, method of separating collections of big sagebrush into the previously described groups was detected during the course of the study. Viewed directly under ultraviolet light, methanol extracts fluoresce in distinctive colors based on the relative brilliance of the phenolic substances already described in the chromatographic analysis (table 3). Young (1965), Winward (1970), and Brunner (1972) have used thin-layer chromatography to distinguish *Artemisia* taxa.

The chromatographic spots that exert the greatest influence on composite coloration are 9, 5, and 6. Where spot 9 is large and brilliantly iridescent and 5 and 6 are only lightly colored (*vaseyana* Ia and *vaseyana* Ic), the extract is a brilliant creamy-white to bluish-white. However, when spots 5 and 6 are brilliantly colored (*vaseyana* Ib and *wyomingensis* Id), much of the brilliance of 9 is masked. In such cases, the composite color reflects the yellow of these spots and produces varying shades of brownish- and greenish-violet. In group II, where the intensity of spot 9 is much reduced, a corresponding reduction in the blue coloration of the composite mixture occurs that results in a strong violet background. The usefulness of this technique lies in the fact that the group to which big sagebrush belongs can be determined a few hours after collection. Since this determination is only qualitative, extraction of the leaves can begin at the time of collection, thus eliminating the drying time necessary for a more quantitative analysis. Winward and Tisdale (1969) outline a similar technique.

The same method also appears to be effective with seed. Methanol or water extract of big sagebrush seed from each subgroup fluoresces in colors similar to but less intense than those from corresponding foliar material. Consequently, it is a relatively simple procedure to determine the subspecies from which seed was harvested (Taylor and others 1964; Hanks and Jorgensen 1973).

Figures 26-32.--Color photographs of representative thin-layer chromatograms of the methanol-soluble extracts from the leaves of the seven subgroups of *A. tridentata*. The origin is on the left. The bright red band near the solvent front (right) is chlorophyll A. Fig. 26, subsp. *vaseyana* subgroup Ia; fig. 27, subsp. *vaseyana* subgroup Ib; fig. 28, subsp. *vaseyana* subgroup Ic; fig. 29, subsp. *wyomingensis* subgroup Id; fig. 30, subsp. *tridentata* subgroup IIa; fig. 31, subsp. *tridentata* subgroup IIb; fig. 32, subsp. *tridentata* subgroup IIc.



Figure 26
1a



Figure 27
1b

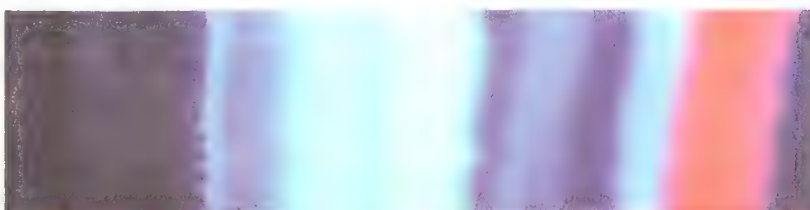


Figure 28
1c

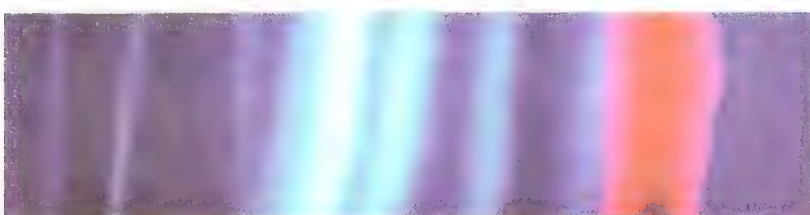


Figure 29
1d



Figure 30
1la



Figure 31
1lb



Figure 32
1lc

DISCUSSION

Evidence for the great plasticity of the *Tridentatae* complex and particularly of big sagebrush, suggested by Hall and Clements (1923) and further demonstrated by the cytogeographic studies of Ward (1953), is substantiated by the large number of chromatographic variants resulting from this study.

Greatest chromatographic variation was observed among collections of big sagebrush; at least seven rather distinct patterns were identified. Considerable additional variation was found among individual chromatograms of collections of this species, but these could not be associated with meaningful patterns. Similar multiple patterns (table 1) and incidental variation were found among collections of other species and subspecies, but none of these approached the apparent chemical diversity of *A. tridentata*.

The most common departure from regular chromatographic patterns seemingly resulted from interbreeding between *Tridentatae* species or subspecies. Chromatograms of progeny from naturally occurring hybrids could be identified by the appearance of spots specific for one parent species in the otherwise normal chromatogram of another species. The most common example of this phenomenon was the occurrence of traces of spot 19 from *A. nova* or *A. cana* subsp. *viscidula* in approximately one-fourth of the *A. tridentata* subsp. *tridentata* and *vaseyana* collections. In support of this contention, Beetle (1960) reported considerable evidence of *A. nova* in the morphological characteristics of big sagebrush populations on the Shivwitts Indian Reservation, Washington County, Utah. Chromatograms of collections from this vicinity, which were included in this study, contained a rather prominent spot 19, which supports Beetle's observation as to close relationship of this form to *A. nova*. Further evidence of past hybridization was the appearance of spot 20, specific for *A. tripartita* subsp. *tripartita* in approximately 20 percent of the collections of subgroup 1a of *A. tridentata vaseyana* (fig. 33). This spot was observed in widely scattered populations of subgroup *vaseyana* 1a from southwestern Idaho to southern Utah. Usually, the introgression shown by chemical patterns



Figures 33-34.--Representative two-dimensional chromatograms of methanol-soluble extracts from the leaves of putative hybrids *A. tripartita* X *A. tridentata* subsp. *vaseyana* subgroup Ia (fig. 33) and *A. tridentata* subsp. *vaseyana* subgroup Ib X *A. tridentata* subsp. *tridentata* subgroup IIb (fig. 34).

could not be associated with morphological characteristics. This type of introgression has wide distribution within the sagebrush populations. Collections taken from ecotones between populations of different species, subspecies, or ecotypes frequently express both morphological and chromatographic evidence of interbreeding.

Chromatographic evidence for hybridization between the following taxa was observed: *A. tridentata* subsp. *vaseyana* X *A. tridentata* subsp. *tridentata*; *A. tridentata* subsp. *vaseyana* X *A. arbuscula* subsp. *arbuscula*; *A. tridentata* subsp. *vaseyana* X *A. nova*, *A. tridentata* subsp. *vaseyana* X *A. tripartita* subsp. *tripartita*; *A. tridentata* subsp. *vaseyana* X *A. cana* subsp. *viscidula*; *A. tridentata* subsp. *tridentata* X *A. tripartita* subsp. *tripartita*; *A. cana* subsp. *viscidula* X *A. tripartita* subsp. *tripartita*. Examples are illustrated in figures 33 and 34. We are confident that many others will come to light as this technique is more widely applied.

Ecological distribution.--The following observations have been made regarding the ecological distribution of the chromatographic groups of big sagebrush, primarily within the Great Basin. Collections of Group I (*Artemisia tridentata* subsp. *vaseyana* and subsp. *wyomingensis*) have come mostly from mountain habitats extending from the upper elevational limits of the big sagebrush zone to, and slightly beyond, the base of the foothills. Specimens of *vaseyana* Ic, which were all collected from the upper elevations of the big sagebrush zone, appear to be widely distributed, as is evidenced by collections of this subgroup (*vaseyana* Ic) from Utah, Idaho, Nevada, Wyoming, and Colorado. *Vaseyana* Ic may include *A. tridentata* subsp. *vaseyana* f. *spiciformis* (Beetle 1960; Winward 1970). The distribution of *vaseyana* Ia extends downward from the *vaseyana* Ic zone to the lower foothills, overlapping considerably with *vaseyana* Ic in the upper elevations and *vaseyana* Ib in the foothills. Subgroup *vaseyana* Ib predominates in the lower foothill pinyon-juniper zone and extends into peripheral lowland areas where it overlaps with *tridentata* IIb. It is interesting that Winward (1970) recognized an analogous or perhaps identical taxon to our *vaseyana* Ib in his taxonomic and ecological study of Idaho big sagebrush. He tentatively referred to this taxon as *A. tridentata* subsp. *vaseyana* f. *xericensis*. However, that name has not been validly published (Winward 1970).

Subgroup *wyomingensis* Id (which occurs in Wyoming, Montana, southern Idaho, northern Nevada, and northern Colorado) overlaps *vaseyana* Ib, the lower end of *vaseyana* Ia, and to a greater extent, the upper end of *tridentata* IIb. Beetle and Young (1965) maintain that *A. tridentata* subsp. *wyomingensis* is intermediate in ecology, morphology, and distribution between *A. tridentata* subsp. *vaseyana* and *A. tridentata* subsp. *tridentata*. Our chromatographic data (table 1) support their recognition of subsp. *wyomingensis* as a valid separate subspecies and corroborate Young's (1965) thin-layer chromatographic evidence for three subspecies. However, our data indicate that subsp. *wyomingensis* has closer affinities to subsp. *vaseyana* than to subsp. *tridentata*.

Table 4.-- Flowering dates of *A. tridentata* subgroups

Subgroup	Flowering date
<i>arceuthobium</i> Ic	July 15-30
<i>arceuthobium</i> Ia	August 5-20
<i>arceuthobium</i> Ib	September 7-21
<i>amblyophylla</i> Id	September 7-21
<i>tridentata</i> IIa	September 7-21
<i>tridentata</i> IIb	September 10-October 10
<i>tridentata</i> IIc	September 10-October 10

One of the primary genetic modifications necessary to permit the development of short-growing-season strains in high elevations is the ability to reproduce under prevailing conditions. Of interest in this regard is the early flowering of *arceuthobium* Ic and *arceuthobium* Ia in contrast to the other subgroups. All seven subgroups are growing together at Snow College Field Station, Ephraim, Utah (5,600 feet elevation). Here, *arceuthobium* Ic blooms as early as mid-July and *arceuthobium* Ia by early August, whereas the other subgroups are not in flower until after the first week of September (table 4). Phenological data presented here are in general agreement with observations from uniform gardens in northern Idaho (Winward 1970) and south central British Columbia (Marchand and others 1966). The Canadian investigators found, as we did, early- and late-flowering ecotypes of *A. tridentata* subsp. *arceuthobium*.

The dominant low-elevation valley big sagebrush (*Artemisia tridentata*) of the northern Great Basin is *tridentata* IIb; in the southern Great Basin, however, *tridentata* IIc is the common low-elevation valley big sagebrush. Small populations of IIc can frequently be seen throughout the Great Basin as tall shrubs growing along fence rows or in other protected areas. *Tridentata* IIb predominates in most low-elevation big sagebrush sites, but it is not confined to these areas; it can be found elsewhere in small populations intermixed with *arceuthobium* Ia and *arceuthobium* Ib types, particularly in the lower foothill areas.

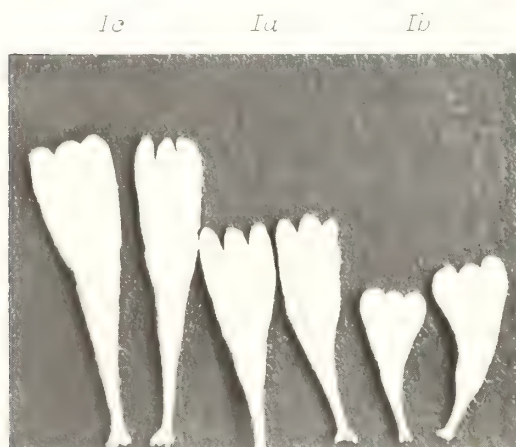
Subgroup *tridentata* IIa was collected only from localized areas of northwestern Nevada where it grows in close association with *A. tridentata* subsp. *amblyophylla* (Id). In fact, chromatographically, it appears to have arisen from hybridization between *amblyophylla* Id and *tridentata* IIb since it contains characteristics common to both (fig. 6).

There is abundant chromatographic evidence that where populations of subgroups overlap and intermix, interbreeding occurs. This is particularly evident in ecotonal areas between populations of *arceuthobium* Ib and *arceuthobium* IIb; chromatograms of specimens contain unusual combinations of spots not found in isolated, uniform populations of either subgroup (fig. 34).

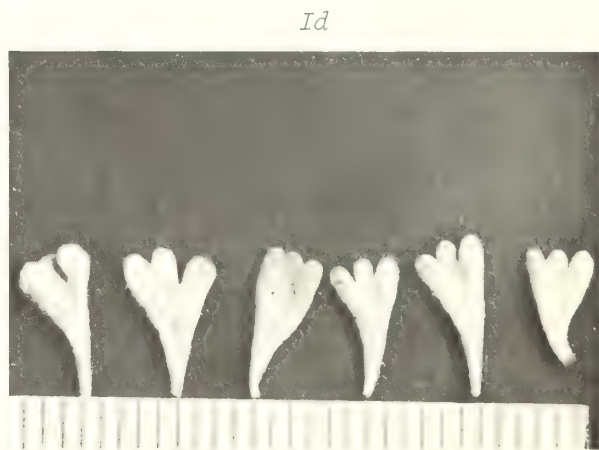
The distribution of subgroups is so uniform within the Great Basin that rather accurate predictions as to their presence can frequently be made after considering elevation and topography. However, distribution outside this area appears to be more erratic. For instance, only a few specimens of subgroup *arceuthobium* Ib have been collected from areas peripheral to the Great Basin. Collection sites outside this area, physically similar to those within the Great Basin in which this subgroup is characteristic, are usually occupied by *arceuthobium* Ia, the most widely distributed of the *arceuthobium* subsp. *arceuthobium* subgroups. Furthermore, *arceuthobium* subsp. *arceuthobium* is the

distributed in Wyoming and Montana (Beetle and Young 1965) and extending into Idaho and Northern Nevada, is not common within the Great Basin. Brunner (1972) noted a different ecotype of subsp. *wyomingensis* in the Great Basin. Additional evidence of this change in distribution patterns is the fact that most populations of subspecies *tridentata* in these same peripheral areas bear more chromatographic similarity to *tridentata* IIc than to *tridentata* IIb, even though these populations occupy areas similar to those occupied by *tridentata* IIb within the Great Basin. This conclusion is based on collections from eastern Utah, southern Idaho, and parts of Wyoming.

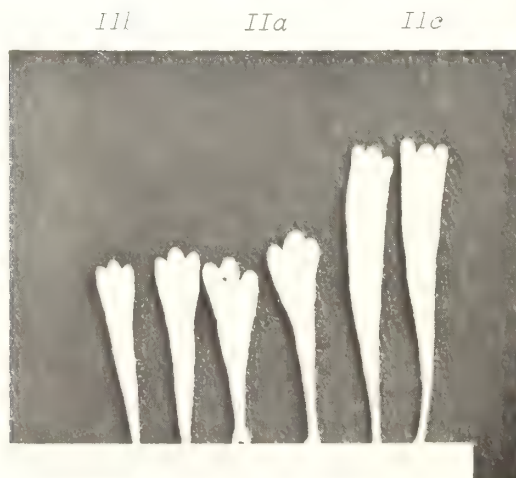
Morphological aspects.--While a thorough morphological study of the seven subgroups of big sagebrush has not been made, the following observations have been noted. The subgroups Ia, Ib, and Ic are undoubtedly variations within the subspecies *vaseyana*. The distribution, the spatulate or broadly cuneate leaf shape (fig. 35), and the pleasant mintlike fragrance of the specimens within these subgroups are all characteristic



35



36



37

Figures 35-37.--Photographs of representative leaves of the chromatographic subgroups of *A. tridentata* (scale is in mm). Fig. 35, from left to right, subgroups Ic, Ia, and Ib of subspecies *vaseyana*; fig. 36, subspecies *wyomingensis*; fig. 37, from left to right, subgroups IIb, IIa, and IIc of subspecies *tridentata*.

of descriptions reported for the subspecies *vaseyana*. However, there seems to be little morphological difference between Ia, Ib, and Ic that can be used consistently to separate them. Odor differences are not sufficiently characteristic to distinguish groups within subspecies. Considerable variation in leaf color has been observed, but similar shades can be found in each subgroup. Leaf size appears to be slightly reduced from Ic to Ia to Ib as the elevation decreases (fig. 35). However, this is believed to be mostly a reflection of the favorability of the site since the difference does not always persist when all types are grown under similar environmental conditions. Leaves of subgroup Id (*A. tridentata* subsp. *wyomingensis*) are cuneate in form and are the smallest in group I (fig. 36).

Similarly, IIa, IIb, and IIc are probably different ecotypes within the subspecies *tridentata*. Leaves of IIa and IIb are cuneate, whereas those of IIc are longer and oblanceolate (fig. 37). Subgroups IIa and IIb appear to be morphologically similar. However, differences have been observed between them and IIc. Plants of subgroup IIc are commonly observed along fence rows, gullies, and similar places throughout the northern Great Basin, but are more common to the south. These plants are typically much taller than those of IIa and IIb, frequently attaining heights of 12 to 15 feet. Although individual plants of large populations of IIc are not generally as tall as those growing along fence rows or in other protected places, they are somewhat taller than similar populations of IIa or IIb. The color of IIc is quite distinct and individuals of this group can usually be distinguished from IIa and IIb by observers acquainted with color variations in sagebrush populations. Plants of subgroups IIa and IIb usually exhibit varying shades of gray green, whereas those of IIc are bluish gray.

The collections studied may not have included representatives from either *A. tridentata* subsp. *vaseyana* f. *californica* or *A. tridentata* subsp. *tridentata* f. *parishii* (Beetle 1960). However, a few long-leaved, high-elevation specimens of *A. tridentata* subsp. *vaseyana* were chromatographed. These collections were chromatographically similar to shorter-leaved *A. tridentata* subsp. *vaseyana* types and are included in *vaseyana* Ic. Furthermore, plants of large stature with drooping inflorescences, a prominent characteristic of *A. tridentata* subsp. *tridentata* f. *parishii*, were collected from the sandy areas of northwestern Nevada. Most of these were chromatographically similar to *tridentata* IIa. We have assumed that these were probably not true *A. tridentata* subsp. *tridentata* f. *parishii* collections.

Distribution in relation to grazing preference.—The two major chromatographic groups, I and II, also show a pronounced difference in palatability. Almost without exception, collections from individual shrubs or populations that normally show signs of heavy grazing by deer and livestock, especially on winter ranges, are included in group I. Grazing preference has been evident for many plants collected from widely scattered areas under heavy utilization at the time of collection. On the other hand, all collections from populations observed to be relatively unpalatable are included in group II. The preference for group I plants, as contrasted with those of group II, was particularly evident in the area from which *wyomingensis* Id and *tridentata* IIa were collected in Nevada and where these two types were growing together as an intermixed population. Form *wyomingensis* Id was highly palatable to cattle that grazed the area, but form *tridentata* IIa was grazed very little. Sheep and deer exhibited the same partiality for *wyomingensis* Id. Similar selectivity of group I over group II has been observed where types *vaseyana* Ib and *tridentata* IIa come together and intermix in lower foothill areas in the Great Basin. Under these circumstances, plants of *vaseyana* Ib are grazed much more extensively than those of *tridentata* IIb. Intermediates resulting from apparent hybridization between these two strains exhibit considerable variation in the degree to which they are grazed, but are usually preferred to the group II plants.

Table 5 illustrates the differential browsing selectivity of deer during April of 1972 for the foliage of several sources from different intermountain areas. Plants from

Table 5.--Utilization by deer of transplanted *A. tridentata* on winter range near Price, Carbon County, Utah

Accession : no. :	Place of origin	: Subspecies	: Subgroup :	Percent : utilization
1601	Hobble Creek, Utah Co., Utah	<i>vaseyana</i>	Ia	60
2201	Indian Peaks, Beaver Co., Utah	<i>vaseyana</i>	Ia	45
4801	Soldier's Summit, Wasatch Co., Utah	<i>vaseyana</i>	Ia	65
5701	Wallsberg, Wasatch Co., Utah	<i>vaseyana</i>	Ib	70
6302	Leonard Creek, Humboldt Co., Nevada	<i>vaseyana</i>	Ib	95
6301	Leonard Creek, Humboldt Co., Nevada	<i>wyomingensis</i>	Id	90
3601	Trough Springs, Humboldt Co., Nevada	<i>tridentata</i>	IIa	35
1501	Indianola, Sanpete Co., Utah	<i>tridentata</i>	IIb	35
1701	Black Mountain, Sevier Co., Utah	<i>tridentata</i>	IIb	10
1703	South of Manti, Sanpete Co., Utah	<i>tridentata</i>	IIb	10
2002 ^{1/}	Marysville, Piute Co., Utah	<i>tridentata</i>	IIb	20
4302 ^{1/}	Gordon Creek, Carbon Co., Utah	<i>tridentata</i>	IIb	35
6704	Dove Creek, Dolores Co., Colorado	<i>tridentata</i>	IIb or IIc	30

^{1/}The common, native big sagebrush on this winter range.

various sources were removed from their native habitats and transplanted into adjacent rows of about 100 plants each on Utah Division of Wildlife Resources deer winter range northwest of Price, Utah (fig. 38). This kind of planting reduces environmental factors (e.g., soil and climate) that might have a confounding influence on utilization.

Although the degree that plants from one source were grazed varied considerably, a strong preference is indicated for group I-type plants as compared to group II-type plants (table 5, figs. 38 and 39). Older but similar plantings that have been grazed by deer and livestock over a longer period of time substantially confirm these observations. We have observed only one instance where grazing animals preferred group II to group I. This exception involved 40 group II plants transplanted from a lowland black greasewood area onto a foothill site having a prevailing group I population. In this instance, deer showed a marked preference for the group II plants. Possibly, the different taste of group II plants in a predominantly group I area attracted the deer.



Figure 38.--Photograph showing transplanted *A. tridentata* for deer browsing selectivity experiments. Arrow, heavily browsed *A. tridentata* subsp. *vaseyana* subgroup Ia accession from Hobble Creek, Utah County, Utah; the two rows to right of arrow, unbrowsed *A. tridentata* subsp. *tridentata* subgroup IIb accession from Indianola, Sanpete County, Utah. Photograph taken January 1971. Note the deer tracks.

Figure 18.--Photograph showing differential deer selectivity in browsing *A. tridentata* from different sources. An *A. tridentata* subsp. *vaseyana* subgroup Ib is on the left and an *A. tridentata* subsp. *tridentata* subgroup IIb on the right.



In summary, *sporophylla* Id and *tridentata* Ib are highly preferred, other *tridentata* subgroups, Ia and Ic, are moderately preferred, and subspecies *tridentata* subgroups IIa, IIb, and IIc are least preferred by grazing animals.

Occasionally, single plants or small groups of plants within large populations of heavily grazed plants are grazed far less than the rest of the population. Several chromatographic analyses have been made when plants that possessed similar morphological characters have been found growing side by side, but one has been heavily grazed, the other ungrazed. In most instances, no important variations in chromatographic patterns were found. However, in collections of this type from lower *A. tridentata* subsp. *vaseyana* (Ib) elevations, chromatograms of the ungrazed plants frequently show evidence of hybridization with *A. tridentata* subsp. *tridentata*, which may account for the difference in selectivity.

Some evidence indicates that reduced brilliance of spot 9 and the appearance of spot 26 in *A. nova* (fig. 19) is also associated with decreased grazing preference. This apparent pattern has not been conclusively demonstrated for all sources. A similar change in chromatographic pattern was observed in *A. arbuscula* subsp. *arbuscula* (fig. 10), but no correlation could be drawn between this characteristic and utilization by game or livestock. Further observations will be required.

Phylogenetic relationships.--Hall and Clements (1923) postulated the evolution of the section *Tridentatae* from the more primitive section *Abrotanum*. They further believed that section *Tridentatae* first gained a foothold in the arid southwestern United States and later moved northward into the Great Basin as climatic conditions became favorable for its expansion into these areas. The connecting link between the sections *Abrotanum* and *Tridentatae* is probably *A. biglovii* (Hall and Clements 1923). *Artemisia biglovii* is a fairly abundant shrub in the upper Colorado and upper Rio Grande River drainages of Utah, Colorado, New Mexico, and Arizona. It produces ray-flowers characteristic of *Abrotanum* and also the trident leaves and overall general appearance peculiar to *Tridentatae*. Support for *A. biglovii*-like taxa as phylogenetic connectors between the two sections, *Tridentatae* and *Abrotanum*, is gained by *A. biglovii*'s intermediate characteristics. Hall and Clements (1923), Ward (1953), and Holbo and Mazingo (1965) place *A. biglovii* in section *Abrotanum*, whereas Moss (1940) and Beetle (1960) place it

in section *Tridentatae*. Chromatograms of *A. biglovii* express a marked resemblance to *Tridentatae* species while demonstrating less similarity toward species of *Abrotanum* (figs. 12, 13; unpublished data²). Consequently, its inclusion in *Tridentatae* is probably the more accurate arrangement and more indicative of its true relationship.

Hall and Clements (1923) also suggest that the parent big sagebrush to evolve from *A. biglovii* was probably *A. tridentata* subsp. *typica* (synonymous with subspecies *tridentata* as described by Ward (1953) and Beetle (1960) and as used in the present paper), principally because it appeared to have adapted to environmental conditions under which *A. biglovii* grew. Chromatographic evidence in the present study substantiates this view and suggests that the parental big sagebrush stock was probably subgroup *tridentata* IIc or unknown taxa having similar chromatographic characteristics to this subgroup (fig. 40). Chromatograms of *A. biglovii* and subgroup *tridentata* IIc are strikingly similar. Spot 9 is small in both, although somewhat more brilliant in *A. biglovii*. Chromatograms of *A. biglovii* contain a large and intensely violet spot 14 and a bright blue-green spot 92. Of the seven chromatographic subgroups of big sagebrush, subgroup *tridentata* IIc alone exhibits this same combination of spots. In all other subgroups, spot 14 is blue to blue-gray and not usually a prominent part of the chromatogram, and 92 is missing. Furthermore, the wide distribution of *tridentata* IIc-type plants in southerly localities where *A. biglovii* is also quite commonly found lends emphasis to the likelihood of a past connection between these two forms. Paradoxically, *A. biglovii* and *tridentata* IIc exhibit little morphological similarity. Biglow sagebrush is a diminutive form, erroneously called black sagebrush by many. In contrast, *tridentata* IIc contains the largest specimens in the section; plants occasionally reach 12 to 15 feet in height. Another significant point that we cannot account for is the fact that grazing animals show high preference for *A. biglovii*, but low preference for big sagebrush *tridentata* IIc.

Subgroup *vaseyana* Ia probably arose as an early variant of big sagebrush and probably represents the parent strain of the present-day subspecies *vaseyana* subgroups (fig. 40). The basis for this conclusion is the chromatographic similarity of this subgroup to other *Tridentatae* species. These include *A. nova*, *A. arbuscula*, *A. cana*, *A. tripartita*, *A. rothrockii*, and *A. longiloba*, all of which purportedly evolved from *A. tridentata*. The common occurrence of a brilliantly iridescent spot 9 in chromatograms of these sagebrush species suggests closer relationship to group I-type plants (*A. tridentata* subsp. *vaseyana* and subsp. *wyomingensis*) than to group II-types where spot 9 is small and exhibits little iridescence. Furthermore, considering the subgroups of group I, none bears greater chromatographic resemblance to these species than does *vaseyana* Ia. Consequently, subgroup *vaseyana* Ia seems to be the branch of big sagebrush arising from *tridentata* IIc and the branch from which other subgroups of group I and most of the section *Tridentatae* evolved. From *vaseyana* Ia-type plants, which occupy an intermediate elevational habitat, subgroups *vaseyana* Ib and *vaseyana* Ic probably arose as modifications respectively adapted to elevational zones below and above that of *vaseyana* Ia (fig. 40).

Artemisia tridentata subsp. *vaseyana* may have arisen before the establishment of big sagebrush within the Great Basin since this form occurs extensively throughout the present range of the *A. tridentata* complex. However, the range of *vaseyana* Ib is largely restricted to habitats within the Great Basin; so this ecotype probably originated within this geographical area.

Our data coupled with that of Beetle and Young (1965) support the hypothesis that *A. tridentata* subsp. *wyomingensis* is derived from subspecies *vaseyana* and *tridentata* of *A. tridentata* and ancestral stock not unlike *vaseyana* subgroups Ia and/or Ib and *tridentata* subgroups IIB and/or IIc (fig. 40).

²David Hanks. 1969 chromatography information on file at Intermountain Forest and Range Experiment Station, Ephraim, Utah.

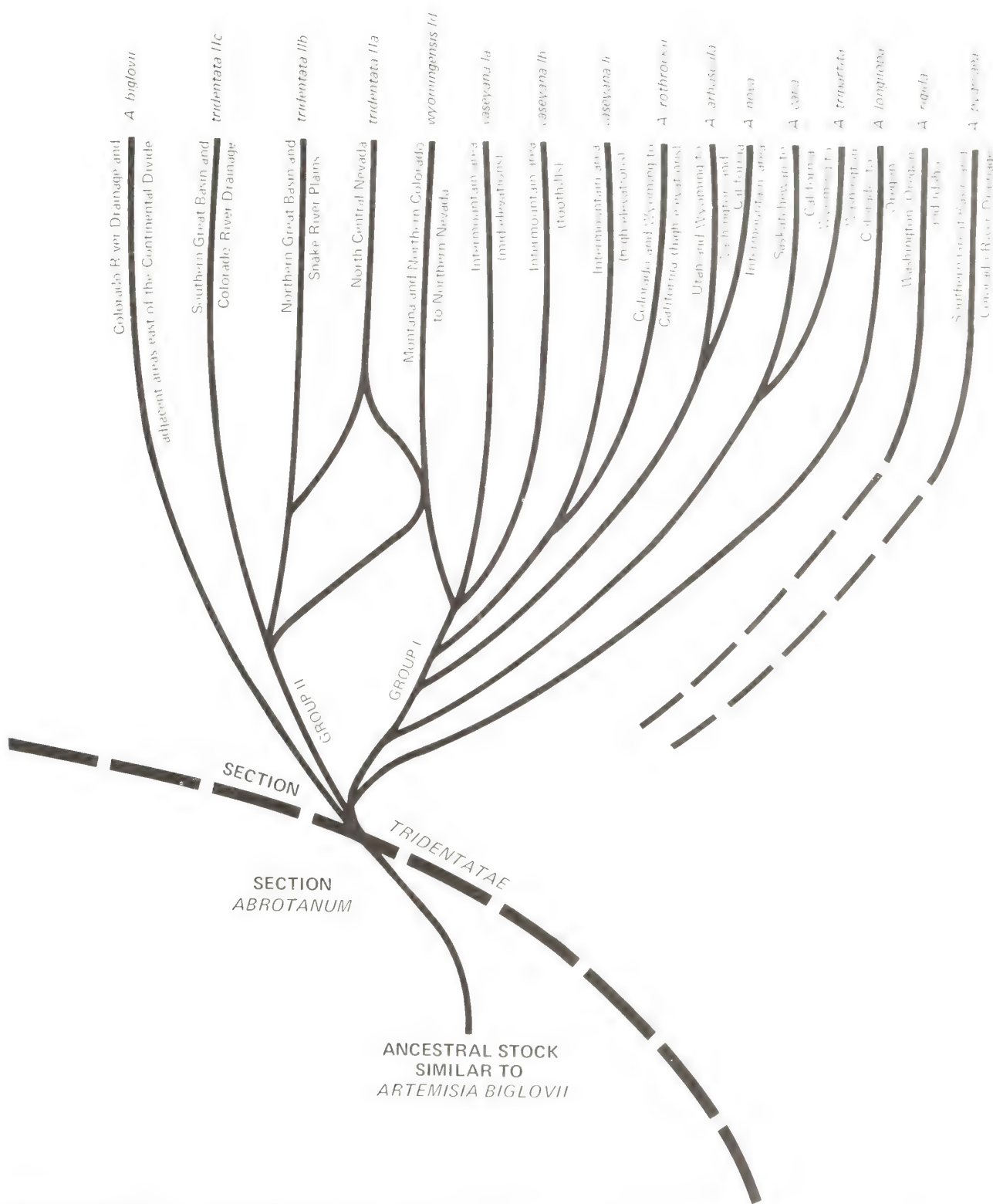


Figure 40.---*Artemisia* taxa and their distributions. Distribution of *A. biglovii* is from Beetle (1960), and the status of *A. tridentata* IIc is from Beetle and Young (1965).

Based on cytological evidence, Taylor and others (1964) postulated the evolution of *A. tridentata* subsp. *tridentata* from *A. tridentata* subsp. *vaseyana* for the British Columbia populations of these two subspecies. In British Columbia, *A. tridentata* subsp. *vaseyana* populations are uniformly diploid, $n = 9$, whereas *A. tridentata* subsp. *tridentata* are all tetraploid, $n = 18$. No introgression between subspecies was observed by Taylor and others (1964) in contrast to the relatively common introgressed populations of the Great Basin. In the Great Basin and adjacent areas, diploid and tetraploid populations of both subspecies occur (Ward 1953; Winward 1970; unpublished data³). No logical pattern of chromosomal evolution is apparent for the *Tridentatae* as a whole either in the Great Basin or over its complete range of distribution. A cytological study should help to clarify the evolutionary past of the Great Basin *Tridentatae*.

The phylogenetic pathway of taxa similar to *A. biglovii* → *tridentata* IIc → *vaseyana* Ia including evolutionary adaptive radiations from subgroups *tridentata* IIc and *vaseyana* Ia is suggested for the Great Basin *Tridentatae* by chromatographic evidence presented here (fig 40). Hybridization-polyploidization cycles such as exhibited in section *Tridentatae* result in reticulate evolutionary patterns (Ward 1953).

Artemisia nova, *A. arbuscula*, *A. cana*, and *A. tripartita* apparently represent two separate evolutionary lines from subgroups *vaseyana* Ia (fig. 40). The latter two species not only appear chromatographically similar to *vaseyana* Ia, but they largely occupy similar habitats. *Artemisia cana* and *A. tripartita* share a common chromatographic spot, 51, which is not found in other *Artemisia* species (table 1). Since it is unlikely that the same spot should have a separate origin in each, these species probably had a common unknown ancestor, or one evolved from *A. tridentata* subsp. *vaseyana* and became the parent of the second. Similar problems are encountered in determining the origin of *A. nova* and *A. arbuscula*. The common ancestry of these two species is suggested by spots 52 and 53, not contained in chromatograms of *A. tridentata* subsp. *vaseyana*, but present in chromatograms of both *A. nova* and *A. arbuscula* (table 1). The connecting link to *A. tridentata* subsp. *vaseyana* may be through either of these species or from an unknown ancestor. The older of these two lines is probably that of *A. cana* and *A. tripartita* since these species exhibit the greatest chromatographic dissimilarity to *A. tridentata* subsp. *vaseyana*. *Artemisia nova* and *A. arbuscula* are more similar to *A. tridentata* subsp. *vaseyana* and so may have more recent origin.

The striking similarity of chromatograms of *A. rothrockii* to those of *vaseyana* Ia and *vaseyana* Ic suggests a close relationship among them (table 1; figs. 2, 4, 23, and 40; Ward 1953; Beetle 1960). Therefore, this species must have evolved from one of the higher elevation subspecies *vaseyana* types, probably *vaseyana* Ic, since the elevational range of this subgroup is nearest that of *A. rothrockii*.

The relationship of *A. pygmaea* to other members of the section *Tridentatae* is not clear. Rydberg (1916) placed this species in a separate section, *Pygmaeae*, although more recent authors (Hall and Clements 1923; Ward 1953; and Beetle 1960) have considered it to be included in *Tridentatae*. Beetle (1960) suggests that it may have an early link with *A. nova*; however, chromatographically, there is no evidence of such a relationship. Chromatograms of this species bear greater resemblance to *A. biglovii* or subgroup *tridentata* IIc than to other *Tridentatae* species (fig. 21). The individual plants of the species tend to be dwarf and usually occur on severe sites impregnated by a fairly high degree of alkalinity.

³E. Durant McArthur. *Artemisia* cytological data on file at Intermountain Forest and Range Experiment Station, Ephraim, Utah.

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HANKS, DAVID L., E. DURANT McARTHUR, RICHARD STEVENS, and
A. PERRY PLUMMER

1973. Chromatographic characteristics and phylogenetic relationships of Artemisia, section Tridentatae, USDA For. Serv. Res. Rep. INT-111, 21 p., illus. Intermountain Forest & Range Experiment Station, Ogden, Utah 84401.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah, (in cooperation with Utah State University)

Missoula, Montana (in cooperation with University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with University of Nevada)



VISITOR PERCEPTION OF WILDERNESS RECREATION CARRYING CAPACITY

George H. Stankey



USDA Forest Service
Research Paper INT-142, 1973

INTERMOUNTAIN FOREST &
RANGE EXPERIMENT STATION
Ogden, Utah 84401



MAJOR FINDINGS

Visitor Attitudes About Use

- MOST WILDERNESS VISITORS CONSIDER LOW INTENSITIES OF USE, INVOLVING ONLY A FEW ENCOUNTERS, AS AN IMPORTANT DIMENSION OF THE WILDERNESS EXPERIENCE.
- THERE IS NOT A UNIVERSAL REJECTION OF PEOPLE. RATHER, MOST VISITORS INDICATED THAT PARTICULAR CHARACTERISTICS OF THE GROUPS THEY ENCOUNTERED, SUCH AS SIZE, METHOD OF TRAVEL, OR BEHAVIOR, WERE MORE IMPORTANT DETERMINANTS OF SOCIAL IMPACT THAN THEIR MERE PRESENCE.
- THE APPEAL OF WHAT WE MIGHT LABEL AS "SOLITUDE" IS A BROAD, GENERIC ONE. HOWEVER, INDIVIDUAL DIFFERENCES IN AREAS (e.g., TYPE OF RECREATIONAL USE, LEVEL OF USE, ETC.) ARE REFLECTED IN THE VARYING DEGREES TO WHICH SOLITUDE IS CONSIDERED DESIRABLE.
- DEFINITE NORMS EXIST REGARDING APPROPRIATE METHODS OF WILDERNESS TRAVEL. IN THE WESTERN AREAS, ALTHOUGH CONFLICTS DO EXIST, HIKING AND HORSEBACK TRAVEL ARE GENERALLY CONSIDERED APPROPRIATE BY USERS AND THIS COINCIDES WITH MANAGEMENT GUIDELINES. HOWEVER, IN THE BWCA, SERIOUS CONFLICTS EXIST BETWEEN CANOEISTS AND MOTORBOATERS: WHAT IS APPROPRIATE IN TERMS OF THE WILDERNESS ACT IS NOT APPROPRIATE IN THE VALUE STRUCTURE OF MANY USERS.
- CONFLICTS BETWEEN GROUPS ARE OFTEN ENHANCED BY THE LACK OF A SHARED VALUE SYSTEM.
- GENERALLY, HIKERS AND CANOEISTS SHOWED A PREFERENCE FOR ENCOUNTERS WITH OTHER HIKERS AND CANOEISTS AND INDICATED THEY PREFERRED NOT TO MEET HORSEBACK PARTIES OR MOTORBOATERS. HORSEBACK RIDERS AND MOTORBOATERS, ON THE OTHER HAND, WERE LESS DISCRIMINATING ABOUT ENCOUNTERS. THEY GENERALLY INDICATED EITHER A PREFERENCE FOR, OR "DON'T CARE" RESPONSE TO, OTHER TRAVEL METHODS.
- THERE IS AN INVERSE RELATIONSHIP BETWEEN THE DEGREE OF EXPOSURE TO OTHER METHODS OF TRAVEL AND THE EXTENT TO WHICH THESE OTHER GROUPS ADVERSELY AFFECT VISITOR SATISFACTION.
- THE PERCEIVED IMPACT OF A GROUP (BOTH IN AN ECOLOGICAL AND SOCIOLOGICAL SENSE) IS A MAJOR DETERMINANT IN HOW VISITORS DEFINE THE APPROPRIATENESS OF THAT GROUP. A SINGLE PARTY OF 30 PEOPLE WAS SEEN AS MORE OF AN INTRUSION ON THE WILDERNESS EXPERIENCE THAN TEN GROUPS OF THREE PEOPLE EACH.

(con. on inside back cover)

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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Robert W. Harris, Director

THE AUTHOR

DR. GEORGE H. STANKEY is a Research Social Scientist assigned to the Wilderness Management Research work unit, which is headquartered at the Forestry Sciences Laboratory on the University of Montana campus at Missoula. He has been with the Station since 1968. Dr. Stankey received his B.S. and M.S. degrees in geography from Oregon State University in 1965 and 1966, respectively, and his Ph.D., also in geography, from Michigan State University in 1971. He has authored several publications in the field of wilderness management.

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ABSTRACT

Nearly 500 visitors to four wildernesses--The Bob Marshall in Montana, the Bridger in Wyoming, the High Uintas in Utah, and the Boundary Waters Canoe Area (BWCA) in Minnesota--completed a questionnaire designed to obtain data on four parameters of use that could potentially affect capacity standards: (1) Level of use encountered; (2) type of use encountered; (3) location of encounters; and (4) effects of depreciative behavior (littering).

Previous studies have indicated that a diversity of attitudes exists among wilderness users. This diversity makes it difficult for managers to interpret and incorporate visitor desires in decisionmaking because such attitudes may be inconsistent with other constraints the manager must consider.

One portion of the questionnaire was designed to obtain a measure of the extent to which the respondent's personal concept of wilderness coincided with that given by the Wilderness Act. Fourteen aspects of wilderness, defined in the Act, were presented. Those persons whose concepts most closely coincided with that of the Wilderness Act were labeled as "strong purists." It was reasoned that the attitudes of those labeled as "strong purists" are of particular relevance to management in decisions regarding appropriate use levels, use control techniques, and physical improvements of wilderness.

The amount of use a visitor encounters on a wilderness trip clearly influences his satisfaction. Solitude is expected by most persons. Most visitors rejected the idea that meeting other parties was an enjoyable experience. Although there was a generally wide ascription to the norm of few or no encounters, many noted that certain characteristics of the encountered groups affected their satisfaction more than did the encounter per se.

One characteristic cited, for example, was method of travel. In the western areas, conflicts do exist between hikers and horseback parties. Hikers tended to be "purists." The conflict was largely one-sided; horseback groups did not strongly object to hikers. Hikers, however, indicated conflicts with parties traveling with stock. In the BWCA, 85 percent of the canoeists were purists, who strongly resented parties using outboard motors.

Large parties had an adverse impact on visitor satisfaction. Two-thirds of those sampled indicated that encountering a large party reduced the sense of being in a wilderness. Given a choice of meeting one large party during the day or no one else, or of meeting from one to 10 small parties, visitors consistently favored the small parties.

Most preferred encounters on trails as opposed to encounters near campsites. There were indications that (a) people normally expect encounters near the periphery of the wilderness and (b) this expectation seemingly modifies the adverse impact of such encounters. Most preferred campsites that provided solitude.

Two-thirds of those sampled were more disturbed by seeing litter than by seeing too many people. This suggests that certain widely-held value systems exist with regard to wilderness and also introduces the possibility of a hierarchy of stimuli having varying degrees of impact on visitor satisfaction.

No one type of use control technique was favored by a majority of visitors. A mail reservation system, involving a limited number of permits, was the most acceptable. Strong purists tended to be somewhat more favorable to the concept of use controls.

Indirect controls (i.e., modification of wilderness infrastructure, manipulation of access) were more favored than direct controls. Horseback riders were more opposed than hikers to the elimination of trails. Both canoeists and motorboaters favored leaving portages rough; however, motorboaters opposed blocking off access roads to wildernesses.

Sixty percent of the canoeists in the BWCA favored limits on party size; 64 percent of those using outboard motors opposed such limits. Visitors to the three western areas were generally in favor of controlling party size. Strong purists favored limiting party size to a somewhat greater degree than did others.

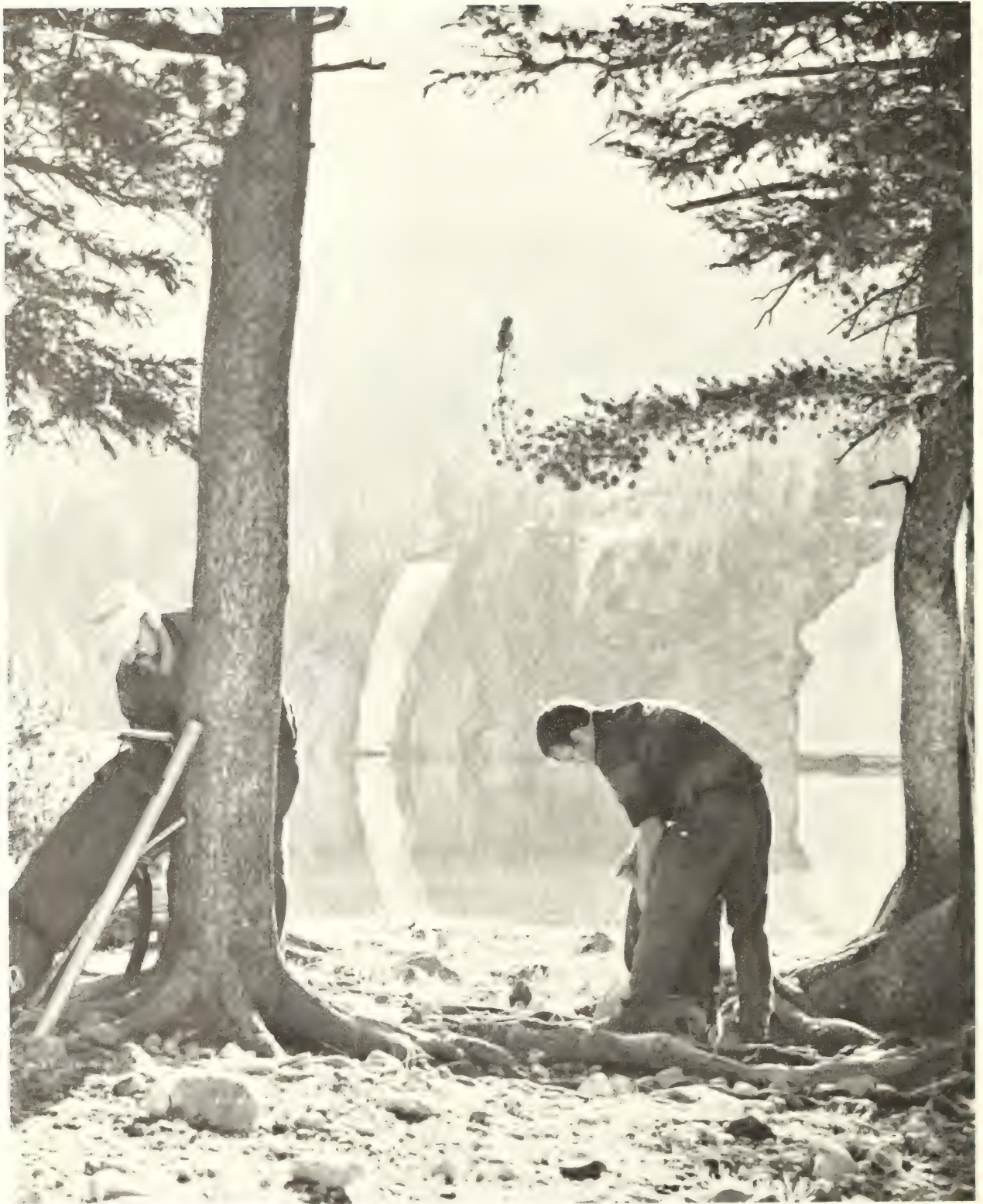
Certain managerial actions designed to protect the resource or provide a more even distribution of use could offset potentially adverse impacts on the wilderness environment. However, most of these actions were opposed by visitors. Physical modification appears to be an unacceptable method of enhancing carrying capacity. Provision of more maps and brochures, and use of wilderness rangers were well accepted methods of influencing wilderness use.

About one out of four visitors felt the wilderness they visited was crowded. Strong purists showed even more sensitivity: about one-third felt the area was crowded. In the BWCA, 40 percent of the canoeists complained of crowding compared to less than 20 percent of the motorboaters. This difference appears related, in part, to the broader definition canoeists gave "crowding," which included both the level and type of use encountered. In the Bridger, about one-third of those complaining of crowding took some action to avoid it. A similar percentage of strong purists tried to avoid the crowding they found.

All four wildernesses had areas defined as crowded. These areas generally were related to well-developed exterior access, scenic attractions, and good fishing opportunities. Visitor definitions of crowding included references to litter, excessive levels of use, and damage associated with livestock grazing.

Several broad types of action are suggested that might increase visitor satisfaction: (1) Limit on party size; (2) better control and cleanup of litter; (3) availability of information and educational materials to inform visitors of other recreational opportunities; (4) a ban on motor craft in the BWCA; (5) a more critical examination of the extent and quality of exterior access to the wilderness; (6) fish and game regulations to control the temporal distribution of use and, to some extent, the type of use; (7) encouragement of "off-season" use; (8) zoning to eliminate conflicts between use types and to protect the resource during critical periods; (9) closure of damaged campsites; and (10) a greater effort to inform the public about the objectives of the National Wilderness Preservation System.

A prototype model to simulate wilderness travel and provide probabilistic measures of encounters is introduced. Although such a model will not make decisions regarding rationing, it will provide administrators with estimates of the consequences of alternative courses of action regarding use control.



Most visitors prefer camping spots near a lake. Estimates of an area's ability to provide a satisfactory wilderness experience may be limited by overnight camping locations on lakes that provide visitors with solitude.

BACKGROUND

This study explores the complex issue of wilderness recreation carrying capacity. Resource managers today find themselves facing difficult decisions regarding the numbers and kinds of use wildernesses can support while meeting the preservation objectives of the Wilderness Act. Decisions that lack a factual basis can lead to irreversible damage to the resource as well as fail to give a quality experience to the visitor. Furthermore, increasing use of the courts by groups dissatisfied with public land management practices stresses the need for decisions based upon the best scientific data available.

Carrying Capacity Concept

Carrying capacity is a fundamental concept in resource management. Traditionally, its primary use has been associated with activities such as range management. Basically, it is the concept that various environmental resistance factors set limits beyond which no major increases in the dependent population can occur (Odum 1959).

The term has some intuitive appeal to recreation management; it has become, in fact, a common, if not agreed upon, part of the recreation management terminology (Chubb and Ashton 1969). Of course, recreational impacts on the physical-biological features of a site are analogous in many ways to the impact of grazing on the range resource. However, in the context of outdoor recreation, we are not only interested in the response of the biological parameters of the site, but also in how the recreational experience changes. When we consider the recreational experience and its relationship to the carrying capacity concept we can again conceive of an output subject to change under increasing use pressure.

The underlying fact of *change* is basic to a grasp of the carrying capacity concept. Any use results in change; for example, we know that fairly low levels of use can lead to marked changes in the biological regime (Frissell and Duncan 1965). The social quality of a recreational experience also is subject to swift and substantial changes in the face of increasing use. The fundamental question in studying carrying capacity is "How much change do we allow?" To answer that question, we must first specify what it is we are attempting to provide; i.e., the management objectives must be clearly defined.

Traditional models of carrying capacity have been founded on two major assumptions. First, it has been assumed that increasing use resulted in a declining quality of output, whether measured in terms of the recreational experience or environmental quality. However, evidence suggests this assumption is false. For example, studies of the biological impact of recreationists on sites have revealed that vegetational changes at recreation sites vary in complex ways that do not correspond with the simple linear model of change expected. LaPage (1967) found that some measure of recreation use other than simple use intensity was required to explain camping impact on vegetation. Vegetation in selected California National Forest campgrounds showed an overall improvement

over a 5-year period (Magill 1970). This improvement was attributed to "adjustment" to recreational use.

Similarly, we find that user definitions of quality do not subscribe to any simple linear relationship between use and satisfaction. To the contrary, for some opportunities, visitor satisfaction is enhanced by increasing use (Wagar 1964). As was the case with ecological change, simple use intensities do not appear to be a sufficient predictor of the recreationist's definition of satisfaction. Method of travel is one use parameter that appears to be more critical for many than the level of use encountered (Lucas 1964).

A second major conceptual basis of traditional capacity models has been a belief in the existence of a determinable figure that represented the "capacity" of recreation land (Wagar 1968). This belief in some inherent quality of land to withstand use has had several unproductive results. It has led to a focus of attention on the biological and physical impacts of recreation, often ignoring the social consequences of increasing use pressures. Moreover, the belief in a single capacity has constrained our thinking and imagination in how to deal with overuse problems. Too often we have not adequately considered the potentially fruitful role of a measure such as capital investment to increase an area's recreational capacity. Perhaps most significantly, the belief in a discrete measure of recreation capacity has led to considerable expenditure of resources and energy in pursuit of that value. Because of the simplistic nature of the traditional model of capacity, we have failed to consider some of the complex but fundamental issues in order to resolve the growing disparity between wilderness demand and supply. To accomplish this, a new model of carrying capacity should be considered.

Limits of Acceptable Change

An alternative model of carrying capacity calls for the establishment of limits in the change that may occur in the ecological and social qualities of a recreational opportunity (Frissell and Stankey 1972). This model recognizes the inevitability of change and relates the process of change to various considerations that will assist managers in defining the "limits of acceptable change." As suggested earlier, the management objectives for the area will be a major influence on such a decision. The model as it applies to wilderness is outlined in figure 1.

Although varied sources can lead to changes in the wilderness environment, our attention focuses on those related to recreation use. Moreover, we will address ourselves only to the issues concerning change in the wilderness experience or what we might refer to as the "social side of carrying capacity," although the wilderness resource consists of two interlinking dimensions (wilderness ecology and the wilderness experience).

The need to define "limits of acceptable change" (LAC) for wildernesses stems from the explicit directive of the Wilderness Act that calls for "the preservation of their wilderness character" [Public Law 88-577]. Increasing demand, coupled with limited opportunities for expansion of the supply sector (outside extraordinary levels of capital expenditure), has created conditions in many areas that make the "preservation of wilderness character" extremely difficult. For example, recreational visits to USDA Forest Service Wildernesses and Primitive Areas increased 14-fold between 1946 and 1970; in this same period, designated wilderness acreage increased only about 3 percent. Although estimates indicate substantial growth in the demand sector, the supply of wilderness is distinctly limited. The recent Roadless Area Review conducted by the Forest Service indicated about 55 million acres of *de facto* wilderness acreage existed in the National Forests. An earlier estimate suggested the wilderness system might reach about 47 million acres, or about 2.5 percent of the conterminous United States (Stankey 1971). Thus, the prospect of added acreage to increase use capability is only a shortrun solution for the wilderness system. One should also recognize that adding acres does little to increase capacity in a net sense because present *de facto* areas already sustain considerable use.

SOURCES OF CHANGE

PREESTABLISHMENT INFLUENCES
WORLDWIDE POLLUTION
EXTERNAL INFLUENCES
MANAGEMENT DECISIONS
RECREATION USE

CONSTRAINTS ON DEFINITION

WILDERNESS ACT
ADMINISTRATIVE POLICIES
USER INPUT
ECOLOGICAL INPUT
DECISIONMAKER'S PERCEPTION
OF PROBLEM
KNOWLEDGE

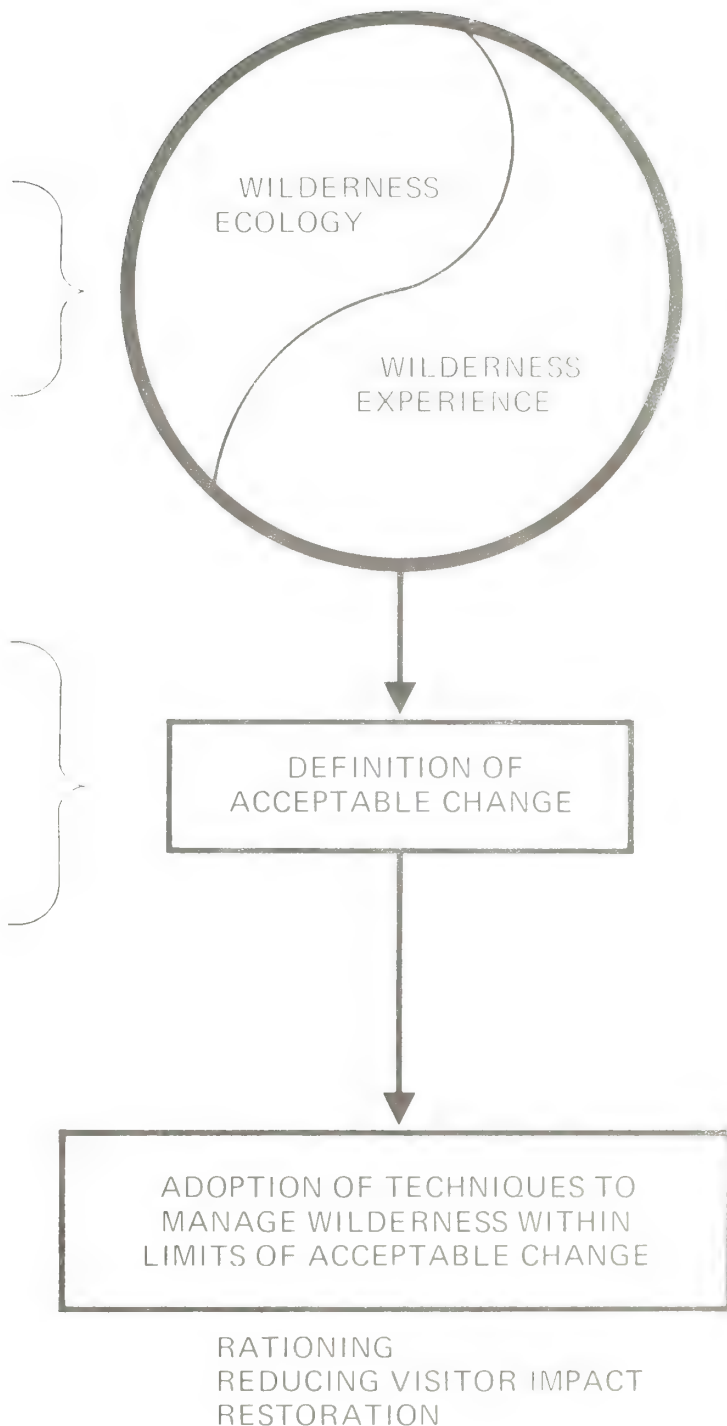


Figure 1.--Model of carrying capacity in wilderness management.



Solitude and the opportunity for a primitive and unconfined kind of recreation are keystones to wilderness recreation.

Providing the type of recreational opportunity described by the Wilderness Act ("Outstanding opportunities for solitude or a primitive and unconfined type of recreation") will be increasingly difficult in the face of the pressures described above. The institution of rationing or of other management measures to offset congestion externalities is a certainty. When considering these measures, however, we are immediately beset by confounding questions as how to measure subjective attributes such as solitude, crowding, and quality.

As a hypothetical concept, we could describe a "pristine wilderness experience" as one offering complete solitude in a completely natural environment, where the visitor will witness no artifact of civilization. Of course, we know present Wilderness does not provide such an opportunity; different areas provide varying degrees of departure from this construct. However, at what point does departure from this construct lead to excessive change in the experience offered the visitor?

Visitor perception of wilderness quality could be influenced by three broad factors: (1) Recreation use-related influences; (2) environment-related influences; and (3) management-related influences. Our interest here focuses on the first category (use-related influences), which we can break down into four principal problem areas: (1) Level of use; (2) type of use; (3) spatial-temporal variations in use; and (4) depreciative behavior. By probing user definitions of carrying capacity, we can focus attention on some of the fundamental research issues to be considered in defining the limits of acceptable change.

Sociological Aspects: Conceptual Issues

The amount of use encountered represents an obvious source of impact on visitors, but little is understood about its specific effects. Are there thresholds of sensitivity toward other users, levels of use that, when exceeded, result in an appreciable loss of quality for the visitor? What is the source of impact for the visitor; is it the mere presence of others or perhaps more subtle influences that are somewhat independent of use levels? To what extent is the absence of meeting other users considered to be an important component of the wilderness experience? To what extent do encounters provide intergroup social interaction that enhance the visitor's experience? What is the nature of the differences (if any) between intergroup and intragroup social exchange?

A second parameter of interest is the type of use encountered. An obvious variable is method of travel. What is the nature of the conflicts (if any) that exist between different travel methods? Again, are there thresholds of sensitivity toward other kinds of groups? In what way do conflicts relate to the predominant method of travel in an area? Does continued exposure to other travel methods generate increased tolerance toward them? To what extent does the type of group one is traveling with influence his perception of other groups?

Encounters vary not only in number and kind, but also in space and time. How does the location of an encounter vary in its impact on visitor satisfaction? Does the user develop some sort of "mental map" of the wilderness which recognizes that certain kinds or levels of use are appropriate in some zones and not in others? In what way do encounters on the trail vary in their impact on satisfaction from encounters while camped? Do visitors recognize "trade-offs" between encounters spread evenly throughout some time period and those that are bunched together, leaving substantial periods free of any encounters?

Finally, what role does behavior play in the social carrying capacity system? Are there accepted social norms that govern behavior in wilderness and to what extent do violations of these norms affect other users? How are these norms communicated? And, how do violations of established norms relate to other dimensions of social carrying capacity in terms of effects on visitor satisfaction?



Much of the Bridger Wilderness shows evidence of intense glacial action. Numerous lakes dot the area. The thin soils support only limited vegetation and stock use can have severe ecological impact.

PROCEDURES AND STUDY STRATEGY

The principal objective of our study was to provide some insight into wilderness visitor attitudes toward the use parameters of amount, type, distribution, and behavior. We also sought to probe visitor attitudes toward not only the concept of use rationing, but toward some specific rationing techniques. Finally, we attempted to measure the relationship between actual recreation use encountered and the respondent's perception of capacity. The study was conducted during the summer of 1969.

Four Areas Studied

Four areas were selected for study: The Bob Marshall Wilderness in Montana, the Bridger Wilderness in Wyoming, the High Uintas Primitive Area in Utah, and the Boundary Waters Canoe Area in Minnesota (fig. 2).



Figure 2.--Four study areas were selected providing a broad range of wilderness and use characteristics against which to study carrying capacity.

The Bob Marshall Wilderness

The Bob Marshall Wilderness lies astride the Continental Divide in western Montana on the Flathead and Lewis & Clark National Forests. It encompasses 950,000 acres; it is the largest of the three western study areas, and was designated a Wilderness in 1940. Elevations range from 4,000 to over 9,000 feet along the Continental Divide, which runs north-south through the middle of this wilderness. There is not a large number of lakes, but several river systems flow through this wilderness, including the Flathead system, composed of the South Fork, Middle Fork, Spotted Bear, and White Rivers, which drains the western part of this wilderness. Areas along the South Fork are open and parklike. Some areas adjacent to the North and South Forks of the Sun River, on the eastern side of the wilderness, also are open and parklike.

Over 66,000 visitor-days were recorded during 1969 in this wilderness. Estimates indicate that most travel was by horseback and that nearly 60 percent of this use occurred during the fall.

The Bob Marshall Wilderness is relatively remote from any major population center. However, it is within a 2-hour drive of western Montana's main urban areas: Missoula (50,000), Great Falls (60,000), Helena (22,000), and Kalispell (11,000).

The Bridger Wilderness

The landscape of the Bridger Wilderness is striking and dramatic; extensive glacial action has left its mark. Over 1,300 lakes dot the area. The only major river is the Green River, which drains the northwest end of this wilderness. Along the crest of the Wind River Mountain Range, the Continental Divide forms the north and east boundaries of this 383,300-acre wilderness.

Several permanent glaciers are found along the crest of the Wind River Range. These glaciers, coupled with the rugged terrain of the Wind River Mountain Range, offer some of the best rock and ice climbing opportunities in the conterminous United States. Many of the peaks range between 11,000 and 13,000 feet.

The intense glacial scouring has left much of the area devoid of soil. Vegetation is sparse in many areas; soils are unstable under even limited use in some of the higher basins, especially during early summer.

The Bridger Wilderness is located in western Wyoming, and is even more isolated from any major center of population than is the Bob Marshall. The towns of Jackson (1,000), Lander (4,000), and Rock Springs (10,000) are the only concentrations of population nearby. However, tourist travel in this area is very high--particularly in the summer--primarily because of the proximity of Yellowstone and Grand Teton National Parks, which are 2 hours' driving time northwest.

Over 111,000 visitor-days were recorded in the area during 1969. Estimates indicate that about three-fourths of this use was by backpackers.

The High Uintas Primitive Area

The High Uintas Primitive Area lies on the Uinta Mountain Range in northeastern Utah. Several peaks within this 237,177-acre Primitive Area are over 13,000 feet high. Extensive alpine glaciation has created numerous cirques and tarns.

Unlike the Bob Marshall and Bridger Wildernesses, the High Uintas Primitive Area lies only 50 miles east of a population center of more than half a million people. This includes Salt Lake City, which is the largest of the network of cities between Logan and Provo. The western boundary of the Primitive Area lies only a short distance from State Highway 189, a major route of travel to Salt Lake City.

Over 100,000 visitor-days were recorded in the Primitive Area during 1969; this use was evenly divided between foot and horse traffic. A considerable amount of it was day use.

The Boundary Waters Canoe Area

The Boundary Waters Canoe Area (BWCA) presents a wilderness environment that is very dissimilar to the three western areas. Lakes are a major feature of the landscape, occupying 16 percent of this area's 1,029,257 acres. Local relief within the area is low (500 feet is about the maximum); however, numerous rock outcrops provide scenic variation.

The BWCA lies within relatively easy driving distance of St. Paul-Minneapolis and Chicago. Access directly into the BWCA is extensive; in fact, visitors can drive close to the boundary along much of the area. Users may enter at 70 locations; however, eight of these locations account for nearly 80 percent of the total use.

This area is the only formally designated wilderness in the Midwest; thus, alternate wilderness opportunities are almost nonexistent in this region. Because of this, use pressures on the BWCA are intense.

Recreational use of the BWCA totaled nearly 800,000 visitor-days in 1969, more than any other unit of the National Wilderness Preservation System. A mandatory free-use permit has been in effect since 1965.

Collection of Data

Fieldworkers contacted exiting parties at the trail heads; all persons 15 years old and above were asked to participate. Less than 1 percent refused to cooperate.

To eliminate potential interviewer bias, the visitors were asked to complete the questionnaires themselves. Field personnel were instructed that they should only attempt to obtain the names and addresses of persons who appeared to be "in a hurry." A questionnaire was then mailed to each of these persons. No statistically significant difference existed in responses obtained from those who completed the questionnaires on the spot and those who were mailed questionnaires. A 78-percent return, using two followups, was obtained from the total of 248 questionnaires that were mailed. A one-page questionnaire mailed to those persons failing to complete the more lengthy form revealed no significant difference between respondents and nonrespondents on selected socioeconomic and attitudinal variables.

The use of wilderness trails varies greatly. Therefore, to eliminate the problem of wasting field time on trails where the probability of encountering an exiting party was low, the trail heads were stratified on the basis of probability of encountering a certain number of exiting parties each day. Two categories were defined: *high use trails*, where an average of at least two parties per day could be expected; and *low use trails*, where an average of from one to two parties per day could be expected. *High use trails* were sampled at twice the intensity of *low use trails*.

Actually, only 493 persons were contacted: 362 observations on *high use trails*; 131 on *low use trails*. Kish (1967) noted that sampling rates can differ between strata if such rates are uniform within strata, provided that the *simple* sums of the stratum totals are properly weighted to compensate for unequal sampling fractions. In this study, the sampling ratio between strata was 2:1. Therefore, observations obtained from *low use trails* were duplicated; this resulted in an adjusted sample size of 624.

Construction of the Questionnaire

The questionnaire was designed to provide (a) a description of the party; (b) information regarding previous outdoor recreation and wilderness experiences; (c) attitudes and perceptions toward various parameters of wilderness recreation use; (d) attitudes toward possible management alternatives regarding wilderness carrying capacity; and (e) a socioeconomic description of the respondent. Data from (c) and (d) form the focus of this paper.

Two sets of attitude statements were developed.

First, 18 items were constructed that focused on (a) attitudes toward encountering various *levels* of use in the wilderness, (b) attitudes toward various *forms* of use in the wilderness, and (c) attitudes toward various wilderness management policies. A five-point scale was provided for each item, ranging from "strongly agree," to "strongly disagree."

Second, 14 items were constructed as follows to meet the need for a unit of analysis that would recognize the wide range of individual involvement, concern, and knowledge about wilderness among the respondents:

- | | |
|--|--|
| 1. Absence of manmade features, except trails | 8. Stocking the area with kinds of fish that were not native to the area |
| 2. Lakes behind small manmade dams | 9. No motorized travel by visitors |
| 3. Gravel roads | 10. Forests, flowers, and wildlife much the same as before the pioneers |
| 4. Private cabins | 11. Solitude (not seeing many other people except those in your own party) |
| 5. Stocking the area with kinds of game animals that were not native to the area | 12. Covers a large area (at least 25 square miles) |
| 6. Developed campsites with plank tables, cement fireplaces with metal grates, and outhouses | 13. Remote from towns or cities |
| 7. Lots of camping equipment to make camping easy and comfortable | 14. Little evidence of other visitors before you |

Ten of the items concerned three basic dimensions the Wilderness Act defines as integral elements of wilderness: (1) Natural ecosystem; (2) a minimum level of human influence; and (3) primitiveness of the recreational opportunity. The remaining four items related to (a) solitude; (b) little evidence of other visitors, (c) remoteness of wilderness from urban areas, and (d) size of wilderness.

Lucas (1964) used method of travel as an approximate surrogate of the respondents' attitudes about wilderness. The Wildland Research Center (1962, p. 135) utilized prior wilderness experience as "a rough and admittedly partial measure of commitment." Both of these efforts were aimed at differentiating wilderness users in a manner that would enable the land manager to translate user values and preferences into actual management decisions, consistent with ecological and policy constraints.

In another study, an attitude scale was developed to differentiate wilderness users on the basis of the underlying values that govern their attitudes toward wilderness (Hendee and others 1968). The scale consisted of 30 short statements relating to features, activities, and benefits ascribed to wilderness and identifying values that persons having a strong wilderness-purist set of values might hold more intensely than those having a less demanding concept of wilderness. This scale was focused on how users perceived certain features, activities, and benefits of wilderness.¹ The scale developed for use in our study was focused on wilderness as defined by the Wilderness Act. The difference between the two scales is important. Both scales provide operational definitions, but it is difficult to state whether they relate to the same construct.

Respondents replied to the items listed on page 10 on the basis of the item's desirability *in the context of wilderness*. A five-point affective scale, ranging from "very undesirable" to "very desirable," was provided for answering. These responses were accorded values from one to five and a total score was computed for each individual. The possible range of scores was between 70 and 14. Scoring was arranged so that a person who held strong "purist" ideas (i.e., consistent with wilderness as defined by the Wilderness Act) would score high while the person with less intense opinions would score low.

Our scale enabled us to array respondents along a continuum on which polar types were represented on one end by those whose concept of wilderness meshed closely with that prescribed by law and on the other end by those whose definition of wilderness differed markedly from that of the Wilderness Act. This made it possible to evaluate responses to the various questions according to the extent to which the respondent concurred with the objectives laid down by the Act.

Because of this multitude of value systems that exists among wilderness users, any definition of "acceptable change" poses a principal methodological problem. Several studies have shown that a gradient of preferences for environmental experiences exists among wilderness visitors ranging from those for whom natural environment and solitude are essential qualities to those who have little interest in such attributes. If we try to decide what users consider "acceptable" without weighing this diversity of opinion, we can expect that our findings will probably suggest a fairly broad latitude in definition. Thus, a major purpose of this purism scale is to provide a mechanism that accommodates the wide range of user definitions of wilderness so that a more sophisticated analysis of the data can be made.

The respondents were classified into groups on the basis of their overall "purism" score (table 1). Four groups were established: *Strong purists*, persons who scored between 60 and 70 on the scale; *moderate purists*, persons who scored between 50 and 59; *neutralists*, persons who scored from 40 to 49; and *nonpurists*, persons who scored less than 40 points.

The boundaries of these four groups are arbitrary to a considerable degree. For example, in classifying visitors as "*strong purists*," the intent was to group persons who demonstrated a consistently high level of agreement with the Wilderness Act's definition of wilderness. "*Neutralists*" tended to be clustered around the midpoint of the scale. Any classification scheme is arbitrary and variations in the establishment of boundaries will affect results. However, as noted previously, these groupings are intended only to provide a framework for recognizing this gradient in our analysis.

¹The reader is urged to review Hendee's "Wilderness users in the Pacific Northwest--their characteristics, values, and management preferences," U.S. For. Serv. Res. Pap. PNW-61, 1968, esp. p. 24-27.

Table 1.--Number of respondents for each study are grouped using purism scale¹

Study area	Strong purists	Moderate purists	Neutralists	Nonpurists	Total
BWCA	¹ 41(20)	100(49)	52(25)	13(6)	206
Bob Marshall	63(53)	47(39)	8(7)	2(1)	120
Bridger	96(67)	33(23)	14(10)	1(<0.5)	144
High Uintas	48(31)	76(49)	28(18)	2(1)	154
Total ²	248(40)	256(41)	102(16)	18(3)	624

¹Percentage value, based on total number of respondents from the area, is shown in parentheses.

²Percentage value, based on total number of respondents from *all* four areas, is shown in parentheses.

For the student of social science methodology, there is a second problem which perhaps is more significant. The attitude scale we used to derive the purist groups is a multidimensional scale; that is, it taps several distinct attitude domains. For example, it asks about solitude, ecological integrity, and vastness. These are separate domains: any individual responding to them might hold varying attitudes as he moves from one domain to another; e.g., he might fully agree that ecological integrity is very desirable in the wilderness, but that the distance from towns or cities is irrelevant. However, the scores a person obtained on the items in our scale were added together; this served as an index of his "purism." This can only be done legitimately if one assumes the scale is unidimensional; i.e., it measures only a single domain. However, there is little reason to believe "purism" is unidimensional,² as our example shows.

Our "purism" scale can be characterized as an intuitive one. It taps a multidimensional domain and labels this domain "purism" because it seeks to measure the extent to which the individual's definition of wilderness conforms to that of the Wilderness Act, *which is also multidimensional*. Properly, the scale should have been subjected to factor analysis. From this, a true unidimensional scale could have been derived. However, this process would have destroyed the intuitive foundation that underlaid the construction of the scale. The Wilderness Act provides a legal definition of wilderness; it is this definition that governs the direction of management decisionmaking. In effect, the Act defines "the rules of the game." Certainly, if public demand so warrants, the Act may be changed. However, until such occurs, the Act must be considered as the principal source of decision criteria under which wilderness managers operate. Thus, purism, as used in this paper, is an institutionalized idea, not some intrinsic environmental quality or homogeneous sociological domain.

Interpreting Attitude Data

This study focused on attitudes. There are many definitions for "attitudes," but a common theme to most is that attitudes reflect a person's disposition toward some person, object, or thing. If we know someone's feeling about something, we assume his behavior toward it will be consistent with his expressed attitude. This

²For an excellent discussion on the problem of measuring purism on a unidimensional scale, see Thomas A. Heberlein, "Some relationships between theoretical and applied issues in attitude research: the case of wilderness," paper presented to the Annu. Meet. of the Rural Sociological Society, August 1971, Denver, Colorado.

is not necessarily true in life. Therefore, attitudes are useful but imperfect predictors of behavior. Public attitude about litter is a good example; almost everyone is against it, but littering continues.

Nevertheless, determination of visitor attitudes toward wilderness management is an important part of the input for managers. If these attitudes oppose some policy, then institution of that policy would probably cause a decline in aggregate visitor satisfaction. Moreover, management decisions that are contrary to expressed attitudes might result in a gradual shift in clientele, as persons whose values cannot be adequately satisfied under those decisions are "displaced" by others who find the changing character of opportunity more nearly suited to their taste. As mentioned previously, the wilderness manager might feel that an established policy leaves him no option other than to undertake the action, but an understanding of possible user reaction could greatly facilitate its implementation.

Although attitudes are imperfect predictors of actual behavior and sometimes change rather rapidly, they are also characterized by a *consistency* in the manner of expression. Attitudes are not characterized by random, totally unpredictable fluctuations. When such randomness appears, it is often the result of a respondent's interpretation or perception of some object or item rather than any intentional arbitrariness. Designing research to avoid this problem is a complex task, but results of carefully designed survey research can provide administrators with important insight on the goals and objectives of wilderness visitors.

Statistical Tests Used in This Study

Two statistical tests were applied to the data. The measure of association between the purism score and response to various questionnaire statements (ordinal measurements only) was gamma. Gamma measures the proportional reduction in error (PRE) possible in predicting rank order variation in response to the statements from knowledge of an individual's purism score over the potential errors that might be derived if these were random predictions. It ranges in value from -1.0 to +1.0 (Goodman and Kruskal 1954; Costner 1965).

The clustering of respondents near the upper end of the scale (very few nonpurists) precluded the possibility of obtaining any high gamma statistics because of the few low scores to balance the analysis. However, as Hendece and others (1968, p. 72) observed:

....for practical interpretation (in a relative sense) the statements receiving gamma values near the upper end of the distribution...can be considered as strongly associated with wilderness-purist concepts as expressed in the...scores.

The second statistical test utilized was chi-square. Chi-square is used to determine whether actual (observed) frequency distribution between independent sample groups is significantly different from that expected, given the total number in the studied categories and sample groups (Burch and Wenger 1967). A significant difference was defined as one that would have occurred from chance no more than 5 percent of the time (0.05 level of significance). A significant chi-square value is designated by an asterisk in the tables.

The sample population was expanded by 26 percent due to the differential sampling intensity (see p. 9). This process also caused chi-square values to appear somewhat higher than if they had been calculated on the raw, unadjusted sample. To eliminate this possible overstatement of significance, chi-square values shown in this report represent those values derived before expansion of the original sample population. However, the figures in the tables represent the expanded sample.

FACTORS IN CARRYING CAPACITY PERCEPTION

Impact of Encounters

We were concerned with determining whether visitors expected to find solitude in wilderness so we sought to grasp how encounters affected the perception of carrying capacity.

Respondents were asked the degree they agreed or disagreed with the following statement: *"It is reasonable to expect that one should be able to visit a wilderness area and see few, if any, people."*

In the western areas, 77 percent of the respondents were in agreement with this statement; in the BWCA, 67 percent agreed. However, a closer examination of responses from the BWCA revealed that paddling canoeists tended to agree with this statement more than those using outboard motors, as reflected in the following tabulation:

	<i>Paddling canoeists (119)³ (Percent)</i>	<i>Motor canoeists (22) (Percent)</i>	<i>Motor- boaters (60) (Percent)</i>
Strongly disagree	2	9	15
Disagree	4	23	13
Neutral	21	5	13
Agree	55	45	48
Strongly agree	18	18	10

The higher agreement expressed by the paddling canoeists could logically be attributed to: (1) As canoeists penetrate deeper into the area than those using motor-propelled craft (Lucas 1964), the probability of encountering others declines; (2) moreover, 28 percent of the paddling canoeists were classified as strong purists compared to 14 percent of the motor canoeists and 6 percent of the motorboaters.

³Total number of respondents shown in parentheses.

Table 2.--*Purist attitudes (in percent) toward meeting other people on the trail*

Purist group	: Number of : respondents	: Bother : a lot	: Bother : a little	: Enjoy it	: Does not : matter
----- Percent -----					
Strong purists	248	20	40	10	30
Moderate purists	254	13	33	23	31
Neutralists	102	4	30	30	34
Nonpurists	20	0	20	20	60
Total	624	14	35	19	32

Chi square 36.42*, 9 df
Gamma = -0.21

Inasmuch as the purism scale used in this study was constructed using the Wilderness Act as a normative framework in which wilderness could be defined, we feel it was reasonable that one should expect to see few, if any, people in a wilderness. This reasoning is substantiated when comparing the response to this statement by "purists" category: 87 percent of the strong purists agreed, compared to only 71 percent of moderate purists, and 59 percent of the neutralists.

Encounters with other parties can occur at two locations. (1) While en route from one destination to another, or (2) at the campsite. We expected that attitudes toward meeting other people would vary according to whether the respondent was on the trail or in camp. Persons were asked to indicate their reaction to encountering other parties on the trail. Only about one out of five persons (19 percent) indicated they enjoyed it; one-third (32 percent) replied that it "did not matter." However, in the BWCA alone, 29 percent responded they enjoyed the encounters; in the three western areas, only 14 percent so indicated.

The reaction to encounters varied considerably among the four purist groups (table 2). Only about one out of 10 strong purists enjoyed meeting people on the trail. The gamma statistic of -0.21 indicates an inverse relationship between purist score and the degree to which one enjoys encounters. However, there was some variation among the area studies in the responses. In the Bridger and the Bob Marshall, strong purists were less inclined to accept encounters on the trail as a part of their wilderness trip than were strong purists in the BWCA and the High Uintas. Whereas about one out of five strong purists in the BWCA and High Uintas (21 and 17 percent, respectively) indicated they enjoyed trail encounters, only one out of 20 in the Bridger and Bob Marshall so responded.

The trail is, of course, a focal point of movement. While one is on the trail, travel is the normal activity and the expectation that one will meet others in transit might temper adverse reactions. However, while in camp, attitudes toward other parties might be different. Thus, visitors were asked the extent to which they agreed with the following statement: "*Meeting other people around the campfire is important to the experience of any wilderness trip.*"

The pattern of responses to this statement was quite similar to that of the trail encounter question. Only one out of five persons (21 percent) agreed that meeting other people around the campfire was important to the experience and about one-third (34 percent) were neutral. Respondents from the BWCA again tended to be more in

Table 3.--Response (in percent) to "It's most enjoyable when you don't meet anyone in the wilderness," by study area

Study area	Number of respondents	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
----- Percent -----						
BWCA	203	10	23	20	24	23
Bob Marshall	120	2	12	22	32	32
Bridger	144	2	13	19	26	40
High Uintas	154	5	16	28	25	27
Total	621	5	17	22	26	30

Chi square 39.40*, 12 df

agreement than those in the three western areas (28 percent as opposed to 17 percent). However, only 10 percent of the strong purists were in agreement. The association between purist score and the level of agreement showed a somewhat stronger inverse relationship ($\gamma = -0.39$).

Respondents also were asked the degree to which they accepted or rejected this statement: "It's most enjoyable when you don't meet anyone in the wilderness."

About two-thirds of the visitors to the Bob Marshall and Bridger Wildernesses expressed agreement (table 3), as compared to the similarity in responses (about one-half) in the BWCA and the High Uintas. Strong purists tended to respond to this statement in a more positive fashion than did the total sample. Nearly eight out of 10 (76 percent) agreed with the statement.

To determine the effect on satisfaction of the presence of others, respondents were asked to evaluate this statement: "You should see at least one group a day in the wilderness to get the most enjoyment out of your trip."

Only about 25 percent of the total visitors sampled for the four areas expressed agreement. However, there were some differences among the study areas. A greater percentage of the respondents in the Bob Marshall and Bridger (58 percent in each) showed a negative reaction to this statement than those in the BWCA or the High Uintas (30 and 47 percent, respectively). In the BWCA, motorboaters had the highest level of agreement (45 percent), which substantiated Lucas' (1964) earlier conclusions that motorboaters were less oriented to the wilderness resource and probably consider encounters as adding to the enjoyment of their trip.

The pattern of responses between study areas is further clarified in examining the answers of the strong purists. Only 13 percent of the strong purists agreed with the statement, while 26 percent of the moderate purists concurred.

CONFLICTS BETWEEN TYPES OF USE

Method of Travel

The type of use one encounters on a wilderness trip is generally varied. Some persons are hiking, others are on horseback. If conflicts do exist between the different travel methods, then the management goal of maximizing visitor satisfaction is hampered. Visitors were asked to respond to this statement: "Both *hiking and horseback travel are entirely appropriate ways to travel in wilderness areas.*"⁴

Backpackers were less inclined to agree with the statement than were horseback riders. They objected to some conditions that result from horseback use: muddied trails, being forced off trails when meeting parties on horses, and manure on trails.

In the West, most respondents agreed with the statement: In the Bridger, 74 percent; in the High Uintas, 80 percent; and in the Bob Marshall, 92 percent. In the Bridger, foot travel predominates, whereas in the latter two areas, horseback travel predominates.⁵

In the BWCA, the conflict between paddling canoeists and those using motor-propelled craft demonstrated by Lucas (1964) and others (Gordon Lusty Survey Research Ltd. 1968) was substantiated (table 4).

Table 4.--*Perception of appropriateness of manual and motor travel by paddling canoeists, motor canoeists, and motorboaters*

Method of travel	Number of respondents	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
----- Percent -----						
Paddling canoe	119	19	33	22	22	4
Motor canoe	20	15	10	5	35	35
Motorboat	60	0	7	18	47	28
Total	199	13	23	19	31	14

Chi square 44.34*, 8 df

⁴On the BWCA form, "paddling" was substituted for backpacking, and "using an out-board motor" for horseback travel.

⁵In this sample, hikers comprised 85 percent of the Bridger sample. Horseback riders comprised 65 percent of the sample in the Bob Marshall, and 51 percent were in the High Uintas.



Only about one-fourth of the canoeists sampled agreed that both canoeing and motorboating were appropriate ways to travel in wilderness. Canoeists almost unanimously viewed motorboats as an indication use was beyond capacity.

Only about one out of four paddling canoeists agreed that *both* paddling and using an outboard motor were appropriate means of wilderness travel. The strong negative reaction to the statement probably can be attributed almost entirely to the reference to outboard motors. The perceived norm regarding appropriate means of wilderness travel held by the paddling canoeists excludes mechanized travel. However, motor canoeists and motorboaters look upon their own mode of travel as being in keeping with their perception of the wilderness environment.⁶ Moreover, they tend to perceive other wilderness groups as similar to themselves; this might explain the source of at least part of the conflict between these user groups. If motor users extrapolate their attitudes and norms about the wilderness environment to those traveling in nonmechanized craft, their behavior in regard to other travelers might be influenced by their perception of a shared value system, even though no such shared system exists in fact.

Visitors were asked to indicate their personal preference for the different modes of travel they might encounter. Sixty-nine percent of all visitors in the BWCA indicated a preference for seeing paddling canoeists (table 5). Only 15 percent indicated a preference for motor canoeists and 6 percent for motorboats, even though these two groups comprised 42 percent of the sample.

⁶Under the terms of the Wilderness Act, "Prohibition of Certain Uses," Section 5, the use of motor-propelled craft is permitted as a protection of preexisting rights. At the time of this study, over half of the water acreage of the area was open to motorized craft.

Table 5.--Expressed preferences (in percent) for seeing other methods in the BWCA, by respondents' methods of travel

Method of travel	Paddling canoeists			Motor canoeists			Motorboaters		
	Prefer:	Prefer:		Prefer:	Prefer:		Prefer:	Prefer:	
	to meet	not to meet	Don't care	to meet	not to meet	Don't care	to meet	not to meet	Don't care
Paddling canoeist	85	5	12	5	35	60	1	51	48
Motor canoeist	41	1	58	50	0	50	10	38	52
Motorboater	51	2	47	20	2	78	14	16	70
	Chi square 27.61*			Chi square 44.06*			Chi square 55.46*		

Table 6.--Expressed preferences (in percent) for seeing other methods of travel in the

Area	Backpackers			Horseback riders			Hikers with stock		
	Prefer:	Prefer:		Prefer:	Prefer:		Prefer:	Prefer:	
	to meet	not to meet	Don't care	to meet	not to meet	Don't care	to meet	not to meet	Don't care
Bob Marshall	44	14	42	21	42	37	16	14	70
Bridger	78	4	18	38	38	24	29	29	62
High Uintas	51	8	41	33	33	34	15	29	56
	Chi square 30.35*			Chi square .54			Chi square 10		

The overall favorable attitude toward paddling canoeists is clearly recognizable. Paddling canoeists have strong antipathy toward motorboaters, but over 75 percent of the motorboaters preferred seeing canoeists to seeing other motorboaters.

The general "don't care" attitude of a large proportion of the motorboaters probably is a reflection of their less critical attitude about appropriate uses of the wilderness; it indicates their greater interest in the area as an activity setting rather than an experience source. When asked if there was one single activity for which they used the BWCA, 40 percent of the motorboaters answered "yes," compared to only 25 percent of the paddling canoeists and 14 percent of motor canoeists.⁷

In the western areas, preferences for different methods of travel appeared linked to the method of travel that was characteristic of each area (table 6). Nearly half of those persons hiking indicated they preferred not to meet horse parties; however, when asked about meeting other hikers, 38 percent said they preferred not to meet them either. On the other hand, persons on horseback were less concerned about encounters with hikers: 62 percent indicated it didn't matter; only 12 percent said they preferred not to meet hikers. Only 5 percent of those on horseback indicated they preferred not to meet other riders. Thus, conflict between use types appears largely one-sided. Horses do present hikers with certain problems that probably reduce their enjoyment.

⁷Thirty-seven percent of the motorboaters answering "yes" indicated fishing as the principal attraction; 24 percent of the paddling canoeists did so.



Nearly one-half of those persons hiking indicated they preferred not to meet horse parties. Much of the opposition, however, may be associated with large parties traveling by stock.



Large parties have an especially significant impact on visitor satisfaction. Not only do many visitors consider such groups inappropriate in wilderness, but there is also concern about their impact on sensitive wilderness ecosystems.

Effects of Large Parties

Past research efforts (e.g., Wildland Research Center 1962) have suggested that large parties might have severe impacts on user satisfaction. Such an effect could result in any or all of: (1) Perception by other users that such groups are inappropriate in a wilderness; (2) recognition of the ecological damage caused by such parties; and (3) extent to which such groups contribute to feelings of crowding.

To determine how large groups affected the satisfaction of other users, visitors were asked to respond to the following statement: *"Seeing a large party (a dozen or more people from a club, and no party) in the area is a disturbing experience in the wilderness."*⁸

Two-thirds of the respondents concurred with the statement, but there was some variation among the areas: 80 percent in the Bridger; 68 percent in the Bob Marshall; 54 percent in the BWCA; and 69 percent in the High Uintas. Both the Bob Marshall and the High Uintas receive more outfitters than does the Bridger. There seems to be a relationship between the degree of exposure to such groups and tolerance for them. In the Bridger, where much of the travel is in small groups, a norm supporting a small group as appropriate seems widely held; in the other areas, where large parties are more common, norms have apparently shifted to a more tolerant position. Also, persons traveling with large groups probably tend to be more tolerant of similar groups (Jubenville 1971; Merriam and Ammons 1968). Method of travel had no effect on response.

This does not necessarily mean that individual user attitudes toward large parties have changed. Rather it may reflect a change in the clientele. Persons who object to large parties may have moved from those areas experiencing increases in this type of use to areas where use still meets their criterion of appropriateness. In a sense, they have been "displaced." As they leave, a new clientele replaces them, drawn perhaps because of the very changes that lead the original group to move. Conflicts in values can gradually lead to substantial changes of clientele--this process needs to be distinguished from changes in individual attitudes (Clark and others 1971).

The more "purist" users were, the more likely they were to express agreement with the statement (gamma equaled 0.33). About 80 percent of the strong purists considered encounters with large parties as detrimental to their enjoyment.

Sonnenfeld (1966) suggested that man might adapt to various conditions of stress by either heightening or reducing his sensitivity. The response to the "large party" statement tends to support this hypothesis. This would indicate that any effort at formulating a measure of carrying capacity for wilderness might only be valid for a particular area or at a particular point in time.

This conclusion is mitigated when the norms of purists are examined: this suggests that they are less adaptable. It appears that certain values are shared over space; the extent to which they are shared over time awaits data from which trends might be examined. It is perhaps revealing that when we examine the percentage of persons classified as purists in the four areas, there is a rough inverse relationship between amount of use and percentage of purists. Many of the purists formerly using areas like the BWCA may now be found in Canada or other remote areas. Those who still utilize the area may do so because of limited opportunity to go elsewhere, strong personal feelings about the area, or by adopting a pattern of behavior that allows them to avoid problems of congestion (e.g., "off-season" visits, careful selection of itinerary, and so forth).

⁸The fact that groups were referred to as "large" or as from a club might have biased response. The major concern in the design of this section of the questionnaire was to present the respondent with a clear and specific stimulus. However, to the extent to which this was accomplished, we might have obtained a somewhat higher level of opposition than a more ambiguous and undefined approach would have obtained.

Table 7.--User preference (in percent) for a single large party (30 or more persons) or a variable number of small parties (about 3 persons)

Area	One large party	One small party	Don't care	One large party	Five small parties	Don't care	One large party	Ten small parties	Don't care
BWCA	7	70	23	15	60	26	19	48	33
Bob Marshall	4	79	17	24	47	28	36	33	31
Bridger	4	88	8	16	68	16	23	56	21
High Uintas	3	73	24	14	57	29	25	43	32
Average	5	77	18	17	58	25	24	46	30
	Chi square 17.07*			Chi square 12.08			Chi square 17.41*		

One other examination was made of user preference for the size of parties encountered while traveling. Visitors were presented with the following hypothetical situations and asked to indicate their preference for one alternative in each situation:

(1) Seeing one large party (30 or more persons) during the day and no one else, or one small party a day (3 persons) and no one else;

(2) Seeing one large party a day and no one else, or five small parties a day and no one else; and

(3) Seeing one large party a day and no one else, or 10 small parties a day and no one else.

The majority of visitors expressed a preference for a single, small party rather than one large party, and although the percentage favoring five and ten small parties declined, it still remained greater than that expressed for a single large party (table 7). This indicates that a large party has an extraordinarily detrimental effect upon user satisfaction and suggests that respondents might perceive the large party as something more than the simple sum of people in the group; i.e., wilderness visitation in a large group represents a behavior outside the accepted norm.

Large parties generally travel by horse in the western areas; thirty people in such a party would normally have an additional 15 to 30 pack animals accompanying them. Thus, the actual party size might be as large as 60, which would have substantial esthetic and ecological impacts.

USE AND SATISFACTION

To arrive at a measure of how level of use and type of use are related, visitors were asked to indicate how they felt about encountering an increasingly larger number of other parties. Specifically, they were asked to evaluate the question as to their feelings about different methods of travel they might normally encounter. Responses regarding these encounters were made along a five-point scale, ranging from "very pleasant" to "very unpleasant." In this manner, for example, it would be possible to estimate the effect of an increasing number of encounters with backpackers on the visitor's satisfaction.

Analysis of Data

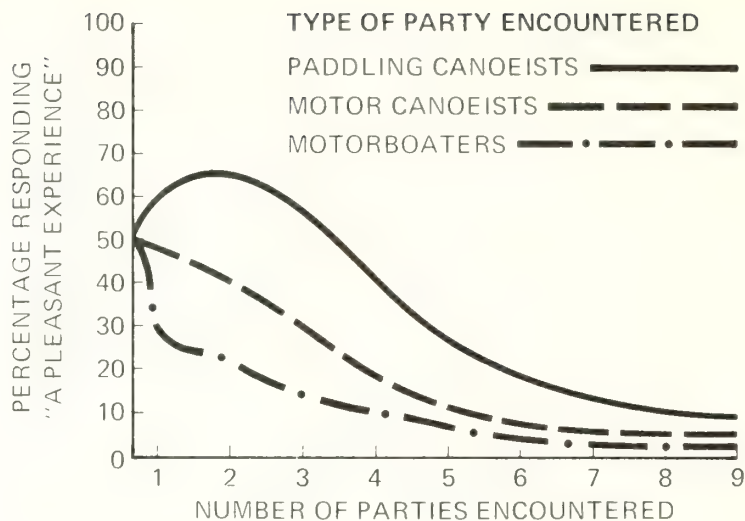
"Satisfaction curves" were computed for each study area regarding various travel methods a visitor might encounter.⁹ The curves were constructed by determining the percentage of respondents in each study area who indicated a "very pleasant" or "pleasant" response to the various encounter situations.

Our general hypothesis that satisfaction declines as use increases was substantiated (figs. 3 and 4). However, certain variations in the slope of the curves are noteworthy. In the BWCA, the method of travel encountered yielded a broadly disparate set of curves (fig. 3). Notice the upswing in the percentage of persons that cited seeing up to two paddling canoeist parties a day as a satisfactory experience. It declines quickly, however, for encounters with persons traveling in motor canoes and motorboats.

The curves obtained for the three western areas combined are shown in figure 4. Note the basic similarity between these curves and those obtained for the BWCA; this suggests that norms regarding use encounters are shared by visitors to all four areas. The unique conditions of individual areas affect the rate and extent of the decline in visitor satisfaction as use increases. Moreover, the perception of carrying capacity for an area is a function of several parameters of which amount of use encountered is only one (fig. 1). Respondents were not fully satisfied even when confronted with situations free of encounters (figs. 3, 4). Therefore, it is obvious that other characteristics (e.g., the physical setting) influence this perception of carrying capacity; we probably never will be able to account for all the variables that influence this perception.

⁹ No curve was computed for hikers with stock because of the small sample size of this group.

Figure 3.--Boundary Waters Canoe Area satisfaction curves.



Characteristics of the individual areas resulted in variations in responses to increasing use. In the Bob Marshall and the High Uintas, these responses varied only slightly between hikers and horsemen. However, in the Bridger, we received more than 30 percent less "pleasant" responses to an encounter with only one horse party than to an encounter with a hiking party.

The curves based upon the responses from only the strong purists in the BWCA are depicted in figure 5 and from the three western areas combined in figure 6. When these two figures are compared with figures 3 and 4, which are based upon the responses of all users, certain consistencies are obvious: Specifically, (1) satisfaction declines with use; and (2) degree of satisfaction is affected by the type of use. However, differences in the degree of satisfaction indicate how the strong purist differs in his attitude toward use compared to the "average" visitor.

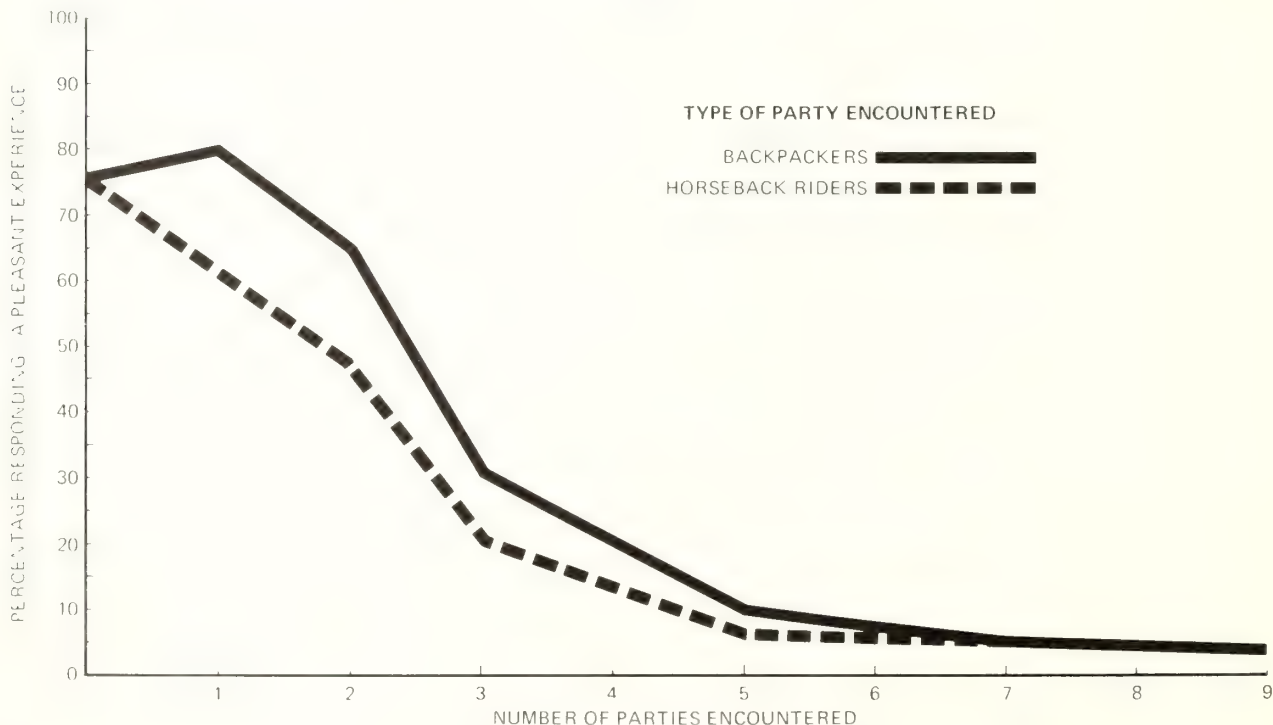
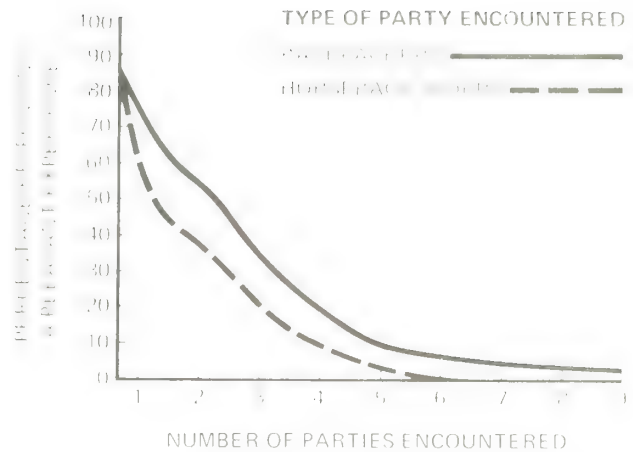
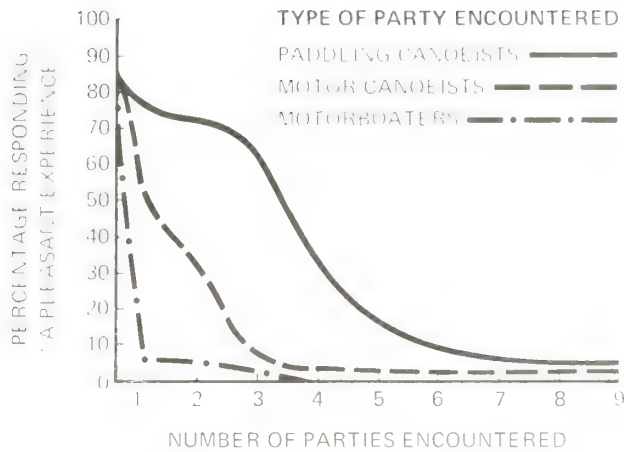


Figure 4.--Satisfaction curves for three western areas.



Initially, these curves reveal the degree to which solitude (seeing no other parties) is an important and differentiating criterion for the strong purists. In all four areas, just over 80 percent of this group preferred a situation free of encounters.

In addition, it is obvious that satisfaction of strong purists consistently declines with *any type* of encounter. There is no upswing in the curve with the first or second encounter as shown in figures 3 or 4; this further confirms our conclusions as to the importance of solitude.¹⁰ However, a majority of purists indicate that over two encounters per day would adversely affect their experience. The latter does not apply to strong purists in terms of their reactions to motorboats. Only 7 percent of the strong purists did not feel that their experience would be adversely affected by one meeting with a motorboat. A similar, but less intense reaction, was obtained from encounters with motor canoes.

Individual area differences will always have to be weighed when prescribing guidelines for carrying capacity. However, individual standards should not be set for each area. Our data indicates that wilderness visitors, particularly the strong purists, ascribe to a remarkably consistent set of standards regarding appropriate intensities of use. Decisions to allow increases in use because of local pressures might lead to a loss in aggregate social benefit as the satisfaction lost exceeds that gained because of the increased number of visitors.

¹⁰The nature of these curves confirms the relationship of use and solitude hypothesized by Wagar (1964).

SPATIAL ASPECTS

The trail head represents a point where entering and exiting parties are focused. Thus, the probability of encountering others is higher than "deeper" in the wilderness. Most visitors are aware of this and expect such encounters in this peripheral area. We hypothesized this expectation would desensitize to some extent possible adverse reactions visitors might experience if these encounters occurred "deep" inside the area, particularly near the campsite. To test this, visitors were asked which of the following they would prefer:

"Seeing a lot of people within the first few miles or so from the road and no one else the rest of the trip or several other parties in the area where I expect to camp and no one else."

More than two-thirds of the total sample indicated a preference for encounters at the periphery of the area rather than in an interior location near camp (table 8). Thus, it appears that users mentally zone wilderness, identifying at least one peripheral region and a core region. Within these zones, expectation of other encounters and the consequent behavior and attitudes toward such meetings differ sharply. This does not suggest visitors *necessarily* enjoy or welcome meetings on the trail. It does indicate most wilderness users, given the option, prefer seeing others while in transit from one point to another, rather than while in camp.

Table 8.--Expressed preference (in percent) for encounters on wilderness periphery or in interior locations

Area	No. of respondents	Encounters on periphery	Encounters in interior	Don't care
----- Percent -----				
BWCA	203	59	14	27
Bob Marshall	118	65	8	27
Bridger	143	76	7	17
High Uintas	152	74	3	23
Total	616	68	9	23

Chi square 17.41*, 6 df

Respondents were asked the extent to which they agreed with the following statement: "When staying out overnight in the wilderness, it is better if there be near anyone else."

There was broad and uniform concurrence with the statement; overall, 75 percent indicated agreement. Purism of wilderness perception was positively associated with agreement with the statement (γ equaled 0.43).

To obtain an indication of how the respondent felt he would react if others set up camp nearby, a situation was described where, after setting up camp in an isolated spot, two or three other parties arrived on the scene.

Visitor reactions to this situation varied sharply. About 30 percent of the total sampled indicated they would keep their camp where it was; either they did not care if other parties camped in the same area or they would enjoy the companionship provided by these persons. However, 65 percent responded that such a situation would result in a loss of quality for them. Reactions by some indicated they would stay at the same campsite, but would experience a loss in enjoyment; others stated they would leave the area and set up camp elsewhere.

Two out of three strong purists in the BWCA and the High Uintas indicated either a loss of enjoyment, a shortened visit, or a search for a new camp as their reaction, as compared to four out of five strong purists in the Bridger and Bob Marshall. This was about the same pattern found for the total sample. As expected, purism was positively related to an expression reflecting a loss in quality (γ equaled 0.34).

User attitudes about others in the same camping area were examined further. Visitors were presented a situation that required them to evaluate how "camping at a place where several other parties are camped" would affect their enjoyment (table 9).

In table 9, it is noteworthy that (a) only 3 percent enjoyed camping near others; and (b) the pattern of response is quite uniform over the study areas. This small variation in attitudes toward other campers suggests that a commonly understood and accepted norm of wilderness behavior exists. This uniformity also applied to the strong purists; about 90 percent of them in all four areas indicated they would be annoyed to some degree by other parties camping near them.

Burch and Wenger (1967) also found an aversion among wilderness visitors to camping near others; two-thirds of their sample indicated a preference for a campsite "far away" from others.

Table 9.--Visitor reaction to persons camping near them.

Area	No. of : respondents	Bother a : lot	Bother a : little	Enjoy : it	Doesn't : matter
BWCA	206	39	40	6	15
Bob Marshall	120	41	43	2	14
Bridger	142	41	44	2	13
High Uintas	153	44	43	2	11
Total	621	41	42	3	14

Chi square 7.85, 9 df

To determine what constituted a desirable campsite, respondents were asked to indicate their preference for one of the following: (1) *A place out of sight and hearing of others*; (2) *a place some distance away from others, but where one might be able to see or hear other parties camped*; and (3) *a place near others*.

Clear differences appeared between the BWCA and the western areas in the response to this questionnaire. Visitors to the BWCA expressed a more ambivalent response to the three options; they split almost evenly on the first two types offered (table 10). Persons traveling with motor-propelled craft tended to prefer camp locations near others. In the West, about two-thirds of the respondents favored locations out of sight and hearing of others: backpackers were slightly more so inclined but no statistically significant differences were detected between methods of travel.

Strong purists in the Bridger and in the Bob Marshall expressed a clear preference for sites providing complete solitude. Eighty-four percent of the strong purists favored this type of site compared to 55 percent of the total sample for the four areas. Although a smaller percentage of the strong purists in the BWCA and in the High Uintas preferred this type of camping location (69 and 75 percent, respectively), they still were decidedly more inclined than the total sample to prefer such a site. The association between purist score and preference for a location out of sight and hearing was relatively strong ($\gamma = 0.52$). None of the strong purists indicated a preference for a site near others. Moreover, less than 20 percent of the strong purists desired a location where others would be some distance away, but still within sight or hearing.

Apparently, the opportunity to be apart from others is an important characteristic of the camping site. It might represent the strong purist's concept of the relationship of man-to-man and man-to-nature in the wilderness. Within the zone around the camp, the primary interaction involves the visitor's group and the physical environment; socialization with persons other than one's own party members is unwanted and probably discouraged. The opportunity to develop close intragroup ties might represent an important dimension of the wilderness experience, particularly when so much of our day-to-day life is characterized by anonymity and impersonalness (Hendee and others 1968).

Table 10.--*Preference (in percent) for camp location*

Region	No. of respondents	Out of sight and hearing	Some dis- tance from others	A place near others	Don't care
----- Percent -----					
BWCA	201	42	37	7	14
West	420	65	27	1	7
Total Average	621	54	32	4	10

Chi square 31.33, 3 df

DEPRECIATIVE BEHAVIOR¹¹

By the very nature of the wilderness environment, where the works and evidence of man are generally minimal, the depreciative actions of users are more noticeable.

Respondents were asked to respond to two aspects of littering: (1) *Their attitudes toward finding litter per se; and* (2) *which groups they felt were littering, or too many persons.*

Persons were asked to indicate their reactions to finding litter along the trails and at campsites. The response was clearly and unequivocally negative. Ninety-nine percent indicated it annoyed them, either a lot or a little.

The response to this item obviously was predictable. However, the item was purposely used to establish the extent to which litter was a source of dissatisfaction.

The overwhelming negative reaction to littering was obtained in a situation where it alone was judged. To test how users felt about litter as opposed to encountering too much use, respondents were asked the extent to which they agreed or disagreed with the following statement: *"Seeing too many people in the wilderness is more disturbing than finding a littered campsite."*

Two-thirds of the sample felt a littered campsite represented a more disturbing situation than meeting too many people. Inasmuch as the statement referred to a "littered campsite," this level of disagreement might have been somewhat intensified because the camp location is important to the user; then littering would represent an especially irritating source of dissatisfaction at this location.

Strong purists did not differ significantly from the total sample in their level of disagreement with the statement. The statement presented a difficult choice for the strong purist, but the similar response of this group to the total sample's response further reinforces the idea that with regard to wilderness certain widely accepted value systems exist. This pattern in the responses introduces the possibility of a hierarchy of stimuli having varying degrees of impact upon user satisfaction; specifically, the results suggest the effects of depreciative behavior (in this case, littering) might override those associated with seeing too many people. Whether this occurs with other dimensions of carrying capacity is conjecture at this point, but efforts should be directed toward investigating this possibility. The presence of such a hierarchy has obvious and important implications in terms of the establishment of management priorities, particularly during periods of limited financial and manpower resources.

¹¹Depreciative behavior, as used here, describes behavior that might violate institutional restrictions, accepted social norms, or both.

VISITOR ATTITUDES TOWARD USE RATIONING

When one considers the increasing use of the limited wilderness acreage and the obligations imposed by the Wilderness Act, it is apparent that some form of rationing will eventually need to be adopted. To many, the idea of regulation seems incompatible with the idea of wilderness. However, the consequences that could occur if controls are not adopted seem similarly unpalatable.

We solicited the attitudes of visitors to a series of techniques that could be utilized by managers to regulate use. These techniques can be grouped into two broad categories: (1) Those that enable the manager to directly ration use; and (2) those that might reduce use by placing greater demands on the potential visitor.

Direct Rationing Techniques

Respondents were asked how they would feel about the use of the five control techniques listed in table 11. No one technique was favored by a majority. However, important differences did exist among the total responses to the individual technique, the responses obtained from each study area, and the responses obtained from strong purists.

Table 11.--*Visitor reaction (percentage of total sample) to use control techniques*

Control technique	: Strongly : favor	: Favor	: Neutral	: Oppose	: Strongly oppose
1. Issue limited number of permits on a first come, first served basis	8	20	18	29	25
2. Issue limited number of permits on a lottery basis.	4	14	20	33	29
3. Issue limited number of permits through a mail reservation system.	15	28	18	19	20
4. Issue permits that assign where people can visit and camp	2	6	11	35	46
5. Charge an entrance fee.	6	17	20	22	35

Visitors strongly rejected assignment of travel and camp itineraries. Approximately 20 percent were neutral in their reaction to the other four control techniques; thus we assumed they might be receptive to the use of such techniques. The ability to directly regulate and manipulate the visitor's trip might have some appeal to wilderness managers, but its regimenting nature and its virtual elimination of the individual's freedom to capture the spirit of spontaneous and unplanned travel apparently make it highly unpalatable to visitors. In many ways, it is the antithesis of the type of experience wilderness is intended to provide.

The mail reservation technique was considered the most acceptable technique of control; six out of 10 were either in favor of it or were neutral. The first-come, first-served technique ranked second; 46 percent of the sample were either in favor of it or were neutral. The greater acceptance of a mail reservation technique seems linked to the relationship between the residence of the visitors and the study area sampled. As an example, 52 percent of the visitors to the Bridger favored a mail reservation technique and only 29 percent supported the first-come, first-served technique. In the Bob Marshall, the order of ranking of these two techniques was the same as in the Bridger, but there was less support for the mail reservation technique (41 percent) and greater support for the first-come, first-served technique (35 percent). The Bob Marshall serves a fairly large local population, however, whereas the Bridger use population is primarily nonlocal. It seems reasonable local residents would tend to favor a technique that requires an individual to report personally to obtain a permit than one where his geographical advantage would be offset by having to apply by mail.

The lottery technique would eliminate many of the advantages and disadvantages associated with an individual's location relative to the particular wilderness he desired to visit. It is, as Hardin (1969, p. 23) notes, "eminently 'fair'."

However, visitor acceptance of a lottery was low; only 18 percent of the total sample favored it. This figure was depressed by its low level of acceptance in the BWCA where only 9 percent supported it. For the three western areas as a whole, 23 percent favored such a technique.

Apparently, most persons are reluctant to leave to chance the opportunity for a wilderness visit. The visitor prefers to retain some control over the outcome, either by personally obtaining a permit or by early mailing of an application. These opportunities are lost in a lottery.

We made no effort to determine what effect the amount of the fee would have on use if the entrance fee technique was adopted. Rather, we were concerned only with user attitudes about the concept of charging for what traditionally had been free.

Only about one out of five persons favored the entrance fee technique. There was a direct relationship between the acceptance of the fee technique and the percentage of each study area's sample having incomes of \$10,000 or more. However, it is probable that factors other than income are involved. Visitors to the Bridger and Bob Marshall areas, for example, consistently showed greater acceptance of all control measures than did visitors to the BWCA and High Uintas.

The pattern of responses from strong purists in each study area tended to be similar to that of the sample, but generally were more pronounced. However, there were some sharp differences between strong purists among the different areas.

Strong purists in the High Uintas were significantly more inclined to accept a first-come, first-served permit system than those in other areas. Situated only 50 miles from Salt Lake City, the area is probably considered by many local visitors, including the strong purists, as "personal property" and a use system that compliments their close location is perceived as more desirable.

Nearly one-third of the strong purists in the Bob Marshall and one-fourth of those in the Bridger favored the lottery technique. This response might reflect a particularly strong level of commitment to wilderness preservation. A number of persons have indicated in personal discussions with me that they would be willing to limit their visits to the wilderness to once every 5 years if it could ensure a high quality visit. The high level of acceptance of a lottery in the Bob Marshall and the Bridger might reflect such thinking.

As was found for the overall sample, strong purists tended to support the mail reservation system most strongly. They vigorously rejected the concept of assignment of itineraries. This suggests that spontaneity and freedom of choice are very important elements of the wilderness trip and not diminished in importance by a person's general attitude toward wilderness. It might also reflect the more common concern about increasing government control over the individual.

Strong purists had mixed feelings about an entrance fee. Although about 45 percent of the total sample's strong purists opposed the imposition of such a fee, the percentage favoring it ranged from 23 percent in the BWCA to 53 percent in the Bridger.

Ordinarily, strong purists adopt a somewhat more positive attitude toward use regulation than do other users. This is a particularly relevant factor for wilderness managers to consider. The strong purists understand that certain aspects of wilderness are being threatened by overuse.

Regulation offers a means of protecting those aspects. However, land managers have consistently overestimated user resistance to controls (Hendee and Harris 1970; Clark, Hendee, and Campbell 1971). Apparently, the converse may be true where important user values are threatened by uncontrolled use; support for regulation can be stronger among users than among managers.¹²

Indirect Rationing Techniques

It might be possible to reduce the total level of use by adopting techniques that would place greater demands upon the visitor's skills or physical stamina. Two potential techniques based on this approach were investigated: (1) Reducing the number of trails and signs (within the area) so that only those persons willing to make the effort could visit the area; and (2) blocking off the last few miles of the access roads so the trail to the wilderness would be longer.

Reduction of Signs and Trails

The reduction or elimination of trail maintenance or elimination of signs, bridges, and other facilities could be considered functional restrictions. No direct restriction would be placed on who or how many might enter. The success of such restrictions is based upon the assumption that total use would be reduced if users were confronted with more primitive conditions of travel where convenience or personal safety became possible considerations. Such success would be contingent upon user awareness of these conditions; this factor was not explored in this study.

Visitor reaction tended to be distinctly more favorable to indirect than to direct restrictions (table 12). About half the visitors to all the study areas either reacted favorably or were neutral to such "restrictions."

¹²Forest Service Region 5 (California) adopted a mandatory wilderness registration system in 1971. Preliminary indications suggest a high level of visitor acceptance of the system, despite the concern by many administrators that it would be strongly opposed.

Table 12.--*Attitudes toward the elimination of trails and signs*

Area	No. of respondents	Strongly favor	Favor	Neutral	Oppose	Strongly oppose
BWCA	205	24	23	16	20	17
Bob Marshall	114	11	18	19	40	12
Bridger	143	24	24	21	22	9
High Uintas	153	14	21	19	30	16
Total	615					
Average		19	22	18	27	11

Chi square 23.45*, 12 df

Visitors to the Bob Marshall and the High Uintas were least favorable in their response; this might be attributed to the large percentage of horseback riders in these two areas. Trails are more necessary for horseback riders than for hikers. The elimination of trails would close off, in effect, certain areas to horses (for example, where one has to cross a talus slope) and would greatly increase the possibility of injuries to the horses. Therefore, it is understandable why in the total sample only about 25 percent of the horseback riders favored this approach.

On the BWCA questionnaire, this statement read as follows: "I am in favor of the elimination of trails and signs in the BWCA."

Surprisingly, persons using outboard motors and paddling canoeists favored such an action to the same degree. It had been hypothesized that those traveling by outboard motor would reject this more subtle control technique because they generally were opposed to any form of control. Furthermore, it would be rather difficult to transport motorized craft across a portage.

Except for those in the Bob Marshall, the strong purists were somewhat more favorable toward reducing the number of trails and signs (gamma equaled -0.23): the more purist the respondent, the more he favored reduction of trails and signs. Only 41 percent in the Bob Marshall favored this action whereas 55 percent in each of the other areas were in favor.

The basically receptive attitude of strong purists toward this form of control was somewhat predictable. It permits such persons to avoid approval of additional restrictions, yet it would tend to alleviate the problem of overuse. Moreover, it promotes a management direction probably similar to the strong purists' own concept of an area where facilities are minimal and where opportunities for cross-country travel are enhanced.

Manipulation of Access

Another method suggested to restrict use involved making the wilderness more remote by blocking off the access road at some point so the hike to the wilderness boundary would be longer. In the BWCA, this would also involve a portage to start the trip.

About 40 percent of the visitors in the three western areas rejected this concept; in the BWCA, 60 percent were opposed. Motorboaters in particular objected to such an action; only 6 percent favored the measure and 14 percent were neutral.

Zoning

Separating incompatible uses in the wilderness has been cited in other studies as a method to provide users with more enjoyable experience (Wildland Research Center 1962; Lucas 1964; Carhart 1961). Even though zoning in the three study areas would apparently have limited value in terms of user esthetics, there may be important ecological reasons for the zoning. For example, areas of particularly fragile soils might have to be zoned against horse use. In the BWCA, on the other hand, zoning areas to exclude out-board motors would contribute greatly to providing a high quality wilderness experience for canoeists.

User attitudes toward zoning were divided clearly between the study areas (table 13). In the BWCA, six out of 10 visitors agreed with the concept of separating travel methods; in the four western areas, only 25 percent agreed.

Apparently, the pattern of response to zoning reflects current administrative practices in zoned areas of the BWCA, where motor-propelled craft are excluded. Handout recreation maps and pamphlets are available to keep visitors informed of these zoned areas.

The responses of strong purists closely followed that of the total sample. In the BWCA, 79 percent favored setting aside areas for the exclusive use of paddling canoeists. Such an attitude reflects the concern of canoeists for the provision of an area that more nearly coincides with their perception of wilderness than does the present legislatively defined BWCA.

Strong purists in the western areas were basically opposed to zoning. About 55 percent of this group in each area disagreed with the statement. However, about one-quarter favored zoning; again it seems the somewhat ambivalent stance of this group reflects their concern for the protection of the resource and their rejection of authoritarian sanctions and controls.

There is no comparable form of zoning in the three western areas. Therefore, the unfamiliarity of visitors in the three western areas to zoning probably contributed somewhat to their negative reactions. Moreover, most of the people apparently cannot perceive the need for such zoning.

Table 13.--*Visitor reaction (in percent) to zoning on basis of method of travel*

Area	: No. of : respondents	: Strongly : favor	: Favor	: Neutral	: Oppose	: Strongly : oppose
- - - - - Percent - - - - -						
BWCA	203	13	14	13	32	29
Bob Marshall	120	20	43	23	13	2
Bridger	144	19	31	15	22	13
High Uintas	154	21	36	18	18	7
Total	621					
Average		18	29	17	22	15

Chi square 79.80*, 12 df

Limit on Party Size

Our study indicated that wilderness users consider encounters with large parties as having an adverse effect on their wilderness experience.

In response to the question, "*Do you feel there should be a limit to the size of parties visiting the BWCA?*" visitors split almost evenly: 49 percent opposed such a limit and 51 percent were favorably or neutrally disposed. However, nearly 62 percent of the paddling canoeists supported such a limit; 64 percent of those using motor-propelled craft opposed it.

Visitors in the three western areas were asked to specify whether they would support a limit on party size and, if so, whether they would prefer such a limit on (a) all parties, (b) horse parties only, or (c) backpackers only. About 70 percent of the Bridger users favored a limit on party size, of which nearly two-thirds favored placing such a limit on all parties. In the Bob Marshall and High Uintas, 30 and 40 percent of the users, respectively, favored restrictions on the size of horse parties. The latter probably can be attributed to the larger percentage of horse parties visiting these two areas.

There was virtually complete rejection of controls of party size for backpackers. Most visitors probably see little benefit associated with such a restriction.

A limit on party size would principally affect the horse party; backpacking groups tend to be small, averaging three to four persons. Thus the responses of backpackers to the proposed party size limit might have been based, in part, on how such regulations would control the size of horse parties. Our analysis of the responses of these two groups provides limited support for this idea; backpackers showed slightly more support for a fairly restrictive size limit (12 people) than did horseback visitors (62 as opposed to 55 percent).¹⁴

¹⁴

This is significant at the 0.05 level, but there is little substantive difference.

VISITOR ATTITUDES TOWARD MANAGERIAL ACTIONS

Respondents were presented with 12 managerial actions (table 14) that could be undertaken to offset potentially adverse visitor impacts.

Table 14.--*Visitor response to suggested managerial actions,
by study area and strong purists*

Managerial actions	Percentage favoring adoption					Gamma ^a
	BWCA	Bob		High	Strong	
	(N=206)	Marshall	Bridger	Uintas	purists	
		(N=120)	(N=144)	(N=154)	(N=248)	
More high quality trails (portages)	37	55	31	35	26	0.31
Signs indicating place to camp ^b	--	52	30	26	31	.41
Portages to lakes presently undeveloped ^c	73	--	--	--	74	.09
More maps and pamphlets	60	52	60	55	54	.05
More campsites	46	22	16	15	17	.39
Wilderness rangers	70	58	68	67	63	.03
Hitching racks ^b	--	26	4	16	10	.46
Small docks at portage landings ^c	24	--	--	--	5	.54
Corrals ^b	--	25	4	11	8	.43
Canoe rests ^c	51	--	--	--	43	.18
Simple pit toilets	63	43	22	25	28	.31
Wooden bridges across large rivers ^b	--	67	65	62	57	.14

^aGamma reflects the degree to which endorsement of the item is related to purist attitudes.

^bListed only on questionnaires used in the three western wildernesses.

^cListed on BWCA questionnaire only.

More High Quality Trails

Recreational use of most wildernesses is poorly distributed in space. If a more even distribution could be achieved, it might be possible to reduce problems of crowding and other conflicts by providing high standard trails which possibly would attract persons to areas receiving little use.

However, the pattern of response suggests such trails are not regarded as appropriate by most visitors, particularly by strong purists. Generally, user attitudes toward upgrading trails are negative: the presence of such trails appears to represent an inappropriate modification to many. Moreover, some visitors might feel that attempting to redistribute use through high standard trails will result in increased use pressures rather than a more equitable distribution.

Response to providing more high quality trails was evenly mixed among those favoring, those rejecting, and those neutral to such an action. However, the more purist users were, the more likely they were to reject such trails. Purists in the Bob Marshall were slightly more inclined to accept high quality trails than purists in the other three areas; this probably can be attributed to the greater amount of horse travel on the Bob Marshall than in the other three areas.

In the BWCA, only about one-third of the paddling canoeists favored more high quality portages; nearly half of those traveling with outboard motors were in favor. Canoeists probably consider such developments inappropriate in wilderness; furthermore, it would facilitate the greater use of many lakes presently reached only by rough portages.

BWCA visitors were asked their reaction to providing portages to lakes previously lacking such access. About three out of four were in favor. However, paddling canoeists tended to be significantly less so inclined ($p > 0.05$); again, it appears they perceive such an action more as promoting the wider distribution of motor craft rather than providing themselves with additional wilderness opportunities.

Signs Indicating Places to Camp

The present pattern of wilderness campsite use is probably influenced considerably by information provided on handout recreation maps of the wilderness area and by the user's past experience; this has concentrated use in only a few areas. Most wildernesses, however, have numerous locations where a small party could set up a tent to enjoy solitude. Often such locations are close to the trail, but factors such as topography prevent the visitor from easily locating such spots. One method of spreading camping use might involve the placement of signs indicating site locations.

The suggested provision of directional signs to campsite locations was not well accepted by visitors, except in the Bob Marshall, where 52 percent responded favorably. There is some basis for horseback riders desiring this kind of information. Visitors traveling by horse are probably less willing than backpackers to chance leaving a trail in search of a nearby camping location.

The general negative reaction to such signs was probably based on the feeling that signs indicate the presence of man; they eliminate the sense of exploration and discovery one might otherwise enjoy.



The provision of high quality maps could do much to enhance the wilderness experience. Information about out-of-the-way camping spots, horse feed, drinking water, and attractions could be shown. Moreover, the availability of such maps would greatly reduce the need for signs.

Maps and Information Pamphlets

An alternative to signs would be to provide maps and pamphlets about attractions, trail quality, campsites, fishing quality, and so forth. Basic interpretative data also could be provided regarding the historical, biological, and geological features of the area. Such printed materials eliminate the obtrusiveness of signs but would require at least some mapreading skills.

Although there was basic agreement to the suggestion of providing printed material, visitor response was not especially favorable. In the total sample, about six out of ten responded favorably; the response among strong purists was slightly less.

This pattern of response suggests that wilderness users do not feel a decided need for printed materials. The author did receive considerable unsolicited criticism of standard Forest Service maps (experience has shown that many such maps are inaccurate, only partially cover trail systems, and are out-of-date). Moreover, it is probable that some visitors fear the availability of better maps will increase total use rather than redistribute use.

More Campsites

Only about 20 percent of the visitors in the three western areas favored the provision of more campsites. Some expressed confusion, because campsites in wilderness are not developed to the degree they are in an auto campground. Often, wilderness campsites are wherever the visitor decides to spend the night. Nevertheless, certain locations have become recognized as campsites, either through administrative actions or through habitual use.

This suggestion was included because an inventory of potential campsite locations based on such criteria as terrain, water supply, and so forth, might be used by managers to redistribute use. However, visitors in the three western areas apparently do not feel the need for such action. Nevertheless, it appears the number of available campsites providing solitude may be a critical "bottleneck" in establishing the esthetic carrying capacity; as such, an inventory of these locations would prove invaluable to the development of management capacity programs. Nearly half of the BWCA visitors favored more campsites probably because they do not have the flexibility that users in the western areas have in finding campsites. As a result of the heavy use on the BWCA, most of the more desirable camping areas are occupied; yet many visitors are probably still hopeful there are other potentially desirable sites.

Wilderness Rangers

Forest Service Wilderness Rangers are on duty on a seasonal basis on all four study areas. On the Bob Marshall, 58 percent of the respondents favored their presence; on the other study areas, approximately two-thirds were in favor. There was no appreciable difference between the response of strong purists and that of the total sample.

Litter cleanup and visitor contact by the rangers probably account largely for their acceptance. None of the visitors indicated they felt rangers were present to "check up" on them.

Hitching Racks and Corrals

Visitors to the three western areas were asked the degree to which they favored the provision of hitching racks and corrals. Half of the respondents opposed both; about one-fifth favored them. Even in the Bob Marshall, only about 25 percent were in favor. Method of travel had little influence on response to this proposal.



About two out of three persons surveyed favored bridges across wide rivers. Purists tended to be less favorable, however.

Hitching racks and corrals could help to prevent much of the vegetation loss, muddying, and soil damage found around many campsites as well as to keep such sites free of manure. They would also help to reduce tree damage caused by tethering. However, damage to the environment might become more noticeable if stock was concentrated into relatively small areas. Many persons traveling by horse or with packstock hobble their animals; temporary rope corrals probably would serve as well as permanent structures. Such facilities probably would not be effective in motivating horse parties to use one area rather than another.

Docks at Portage Landings and Canoe Rests

In the BWCA, docks and canoe rests might be considered functional equivalents to hitching racks and corrals in the three western areas. Overall reaction was somewhat mixed; mode of travel did not affect the response. Paddling canoeists were more favorable toward canoe rests, but not significantly so, even though such rests are not used by most motorboaters. Docks were viewed as not being particularly necessary.

Pit Toilets

Despite all other considerations, it might become necessary to restrict use if sanitation problems develop in an area. Human health is not the only reason. Barton (1969) pointed out that the release of nutrients and pollutants associated with increasing recreational use in the BWCA can result in aquatic growth that has adverse effects on esthetics as well as on health.

Visitor response to the provision of pit toilets varied fairly substantially between the BWCA and the western areas; it varied to a lesser degree among the three western areas. This response was expected because sanitation problems are more serious in the BWCA where soil cover is limited and there is more danger of polluting the only source of drinking water because most campsites are on lakeshores. Current management policy in the BWCA recognizes these problems and simple latrines are already being provided. In the western areas, disposal of human waste generally is more easily accommodated. At the time of this study, toilets were still to be found on the Bob Marshall, which might explain the greater level of approval for such facilities in this area. Current Forest Service policy permits the construction of toilets in cases where sanitation is a problem.

Wood Bridges

Nearly two out of three persons favored erection of wood bridges across wide rivers. The basis for this response probably varied among individuals, but the element of safety probably influenced the responses. Such bridges also have potential as a management technique to use in redistributing use. In certain areas, a bridge across a river that cannot be safely forded could provide access into remote areas. Strong purists tend to be less favorable to bridges. This is to be expected because bridges obviously represent the invasion of man and are in direct contradiction to their philosophy that is rooted in virgin landscapes.

In view of existing legislative constraints, as well as of the basically negative attitudes of visitors (especially those of strong purists) toward any physical modifications except bridges, one could only conclude that structural modification of landscapes will not appreciably enhance carrying capacity. Claims by administrators that such developments are necessary because visitors "want this" or "demand that" appear unfounded. Such statements may stem more from administrators' misperception of user desires than from an accurate assessment of users' needs and desires (Hendee and Harris 1970; Clark, Hendee, and Campbell 1971).

RECREATION USE IN RELATION TO CAPACITY

Given an opportunity to respond to questions on the basis of "What should be," wilderness visitors tend to reject excessive numbers of people, certain types of use, encounters at certain locations, and evidence of littering. Do they, in fact, react in the same way under actual conditions? To determine this, some of the specific aspects of the respondent's visit were investigated.

User Perception of Crowding

When asked whether the areas they had visited seemed "crowded," about three out of four replied "No." However, 24 percent indicated they encountered "crowding;" specifically, they felt the character of use encountered did not provide a high quality wilderness experience, an implicit management goal of the Wilderness Act.

However, response to this question varied greatly among study areas and the users. Visitors to the Bridger were most critical; 33 percent felt crowding was a problem. In the BWCA (which had the highest use of the four areas), 28 percent of the visitors felt crowding was a problem; in the Bob Marshall (which had the least use of the four areas), only about 11 percent expressed concern over crowding.

Nearly 40 percent of the canoeists complained of crowding; less than 20 percent of those using outboard motors did. This pattern of response can be attributed not only to the canoeists' greater sensitivity to use levels, but also appears to be related to their greater intolerance for outboard motors.

In the West, backpackers tended to complain of crowding to a greater degree than horseback riders; about one in four complained as opposed to about one in six horseback riders. Apparently--as was the case in the BWCA--backpackers' definition of crowding is influenced not only by the level of use encountered, but also by the type of use encountered. Horseback riders appear to define crowding more in terms of amount of use encountered and do not display the adverse reactions toward other types of users as backpackers do.

Paddling canoeists and backpackers were disproportionately represented among the strong purists, and as a consequence, it follows they would be more critical in their evaluation of crowding. This was evident when purist scores were examined as the independent variable. Strong purists perceived crowding to be more of a problem than the other purist groups (36 percent as compared to 17 percent of the moderate purists); gamma between purist score and the degree to which crowding was perceived as a problem was 0.42.

Effects of Crowding on Route of Travel and Length of Stay

Respondents who cited crowding as a problem were asked to indicate whether it had caused them to change the route or duration of their wilderness trip, or both. Separating one's self from an area perceived as crowded, either by changing the planned travel route or by actually terminating the trip early and leaving the area, was interpreted to be the strongest action open to the visitor.

Most visitors simply tolerated situations they perceived as crowded. Overall, 79 percent indicated they took no action to get away from areas of crowding. The Bridger Wilderness was one exception, where only 68 percent were content to tolerate overuse; there, one out of three persons altered their spatial behavior to offset what they considered to be a situation detrimental to their enjoyment.

In the BWCA, only about 10 percent of the persons traveling in motor craft who mentioned crowding as a problem indicated this affected their itinerary. However, nearly 20 percent of the paddling canoeists reacted to crowding by altering the route or length of the trip. This suggests that even though both canoeists and those traveling by outboard motor may perceive problems of crowding in wilderness, the effects are of less concern to the latter group and there is less motivation to try to alleviate its impact. For some of the paddling canoeists, however, crowding represents a serious intrusion upon their experience; consequently, they are more likely to take measures that will offset or eliminate the problem.

The decision to shorten one's trip probably represents a more drastic reaction than changing one's route. Although a change of route might mean the user will not have the opportunity to visit a particular area he was interested in, he may discover some equally pleasing new location. On the other hand, cutting short the length of one's visit indicates the user apparently perceives no other alternative to contend with crowding and terminates his visit.

The Areal Extent of Overuse

Visitors to each area were asked to indicate where crowding had been a problem; we were then able to map each study area showing where visitors considered that use had reached or exceeded their definition of capacity.

An index of crowding (IC) was computed, where $IC = \frac{TC}{TV}$. TC represents the total number of complaints reported by the individuals in any given area (for example, a lake basin) and TV represents the total number of visitors sampled who visited that particular area.

Using the values so computed, we constructed a series of isolines with those line values representing the percentage of individuals sampled who visited a particular area and defined it as crowded. Thus, it was possible to obtain an idea of the areal extent of crowding and its relationship to external access, attractions, and trails.

Overuse and Crowding in the BWCA

About 28 percent of the users sampled in the BWCA complained of crowding. As shown in figure 7, areas of perceived crowding were fairly limited in their areal extent: the Moose Lake area, the Fall Lake entrance, the Saganaga Lake-Sea Gull area, and the Lac La Croix area. The Lake One entry also represents a problem area, but to a lesser degree.

Moose Lake and the Fall Lake entry are the principal problem areas. These two large lakes lie on the BWCA boundary, only a few miles from Ely, Minn. Consequently,

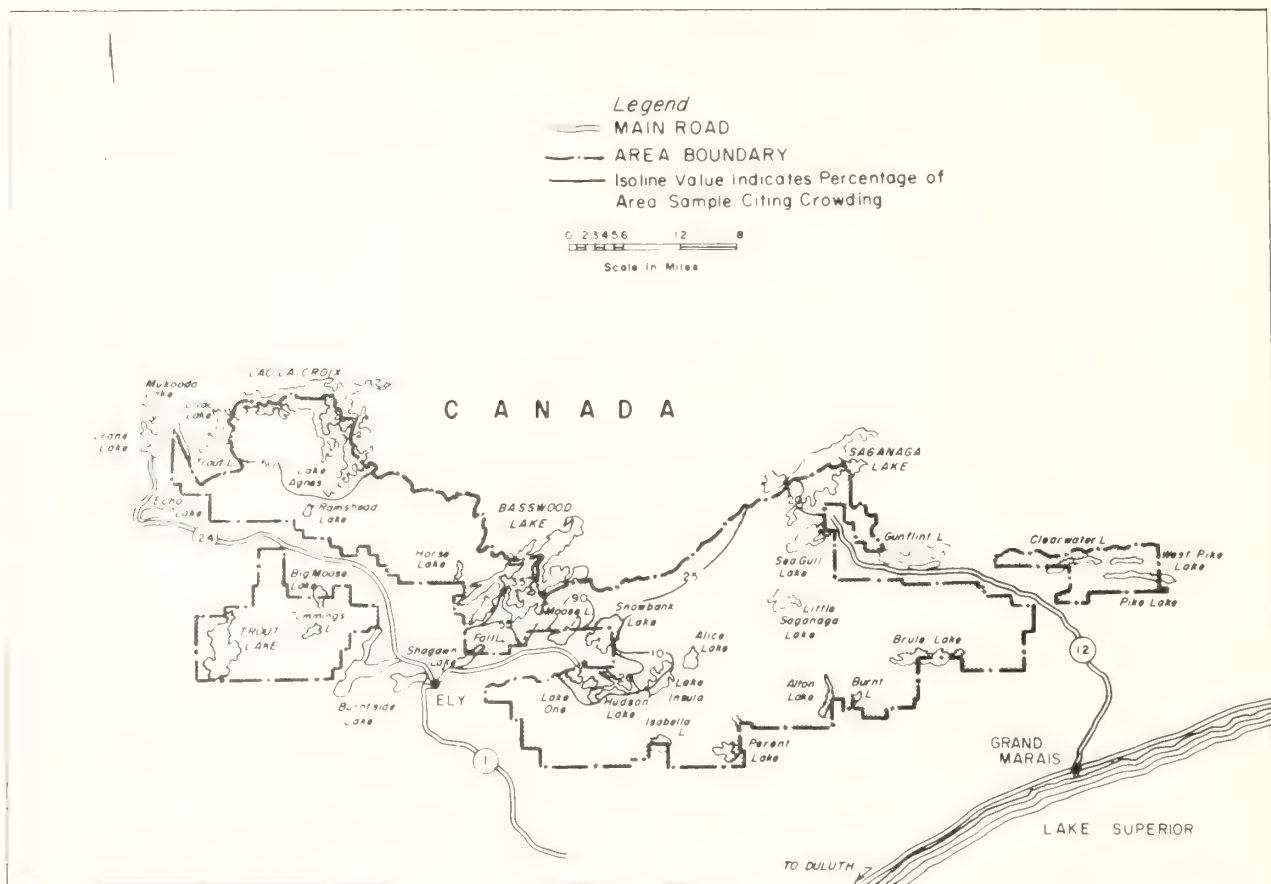


Figure 7.--Zones of crowding within the Boundary Waters Canoe Area.

concentrated use of these lakes is to be expected to some extent, but apparently it has reached such levels that many persons must endure an initial period of dissatisfaction until they have penetrated a few miles into the area, where use begins to disperse and decline.

Except for the Saganaga Lake-Sea Gull and Lac La Croix areas, crowding is concentrated immediately east of Ely. Access into this area is well developed. The Fernberg Road, extending about 20 miles east from Ely, is a paved highway and well-maintained. This will probably tend to intensify the already skewed use distribution.

Both the Saganaga Lake-Sea Gull and Lac La Croix area were classified as "transitional" (they were close to being used to capacity) by Lucas (1964) in terms of the relationship between use and capacity. The lakes in these areas serve as important links for considerable Canadian-bound traffic; as BWCA use increases, it seems reasonable that more persons will have Canada as their destination (Nelson and Hughes 1968). Thus, lakes that presently accommodate a considerable amount of this northward flow can expect future increases in numbers of visitors as well as complaints about overuse.

It was stated earlier that carrying capacity is a function of not only use levels, but type of use encountered, location of encounters, and evidence of depreciative behavior as well. In analyzing comments regarding overuse in the BWCA, a striking number of persons defined crowding in terms of the simple presence of motorboats. Other specific complaints cited littering, campsite wear and tear, and the inability to find isolated campsites.

Visitors indicated that overuse is not uniformly spread throughout the area, but rather that it tends to be focused in certain locales; among the principal locales are around portages from one lake to another. Use is normally constricted in these areas as travel patterns converge into a narrow flow through the portage. One result is that canoeists are forced into contact with the motor craft they usually try to avoid. The result is an increased level of dissatisfaction for these persons.

Overuse and Crowding in the Bob Marshall

In the Bob Marshall Wilderness, two areas were defined by visitors as crowded (fig. 8). One is along both sides of the South Fork of the Flathead River. This area has long been recognized as being overused; in 1970, Flathead National Forest officials closed several camps along the river so vegetation damaged by overuse might recover. The open, flat nature of the country, as well as the attractiveness of the river, has drawn a large number of visitors for a number of years.

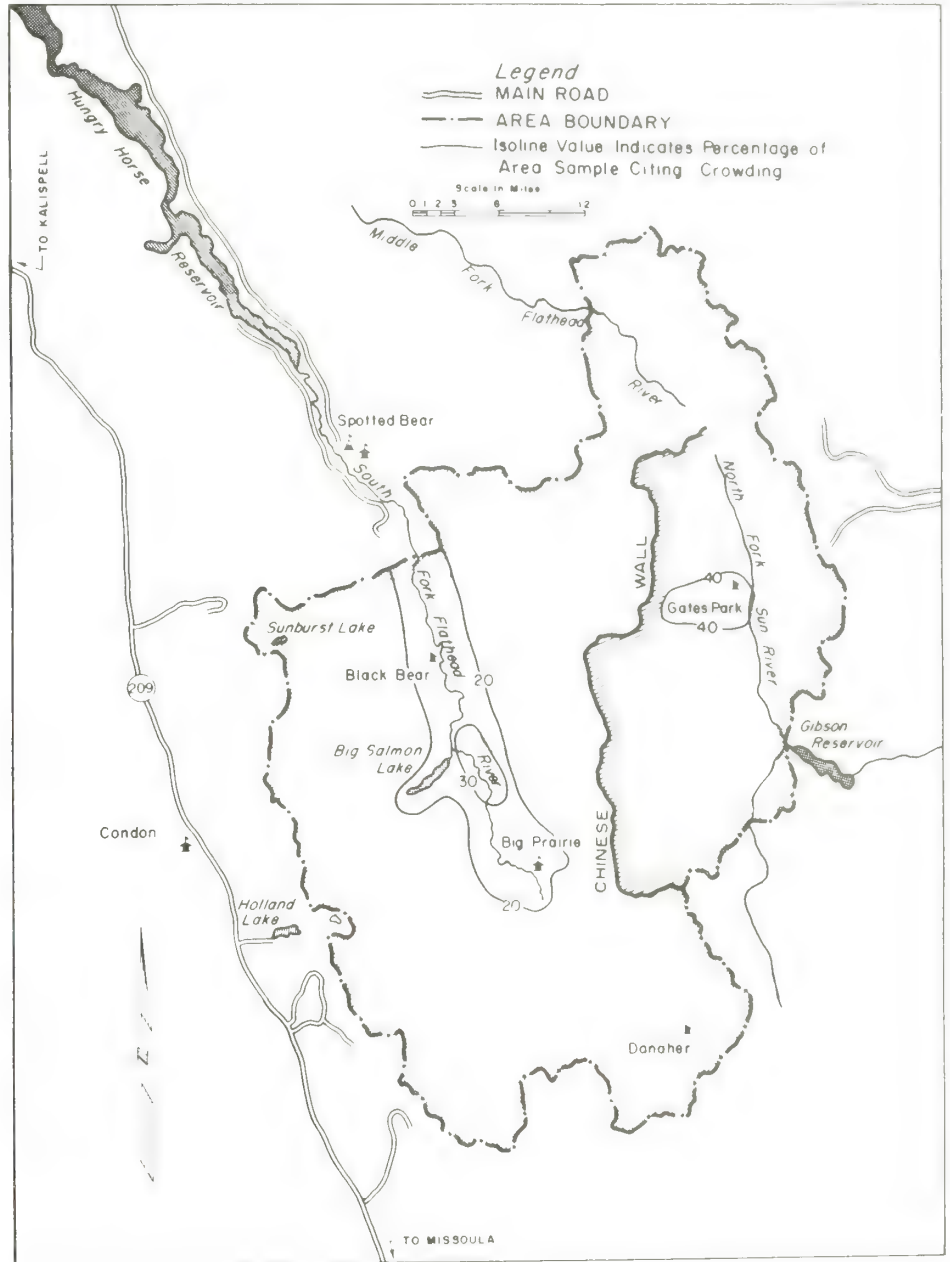


Figure 8.--Zones of crowding within the Bob Marshall Wilderness Area.

The second area was along the east side of the wilderness at Gates Park. Like the South Fork of the Flathead River, this area has sustained moderately high levels of use for some time. Access into this area is either along the North Fork of the Sun River or over Headquarters Pass from the South Fork of the Teton River.

Both of these areas are characterized by not only an apparent problem of excess use, but by a large amount of horse use and by the presence of administrative structures. A Forest Service Ranger Station and an airstrip are located at Big Prairie along the South Fork of the Flathead River. Two other airstrips are located nearby, one at Black Bear and another at Gates Park. These airstrips are restricted to emergency use only; nonetheless, they represent extremely noticeable impacts on the land.

The longitudinal boundary of the zone along the South Fork of the Flathead which was perceived as crowded is a marked departure from the pattern found in the other western areas. In most areas, lake basins form a convenient frame of reference for users' definition of the areal extent of crowding. This longitudinal aspect represents a serious barrier to the goal of managing for high-quality wilderness recreation. As noted earlier, the South Fork is a major artery of travel into the wilderness and it is clear that use levels are such that considerable penetration is necessary before many users find a desirable experience.

Use problems intensify somewhat near Big Salmon Lake and its junction with the South Fork. The attraction of a lakeside camping location and the opportunity for both stream and lake fishing probably make this an especially desirable location. However, it is paradoxical that these very qualities accelerate and accentuate the problems that gradually lower the desirability of the area (e.g., littering, campsite deterioration, too many people).

Overuse and Crowding in the Bridger

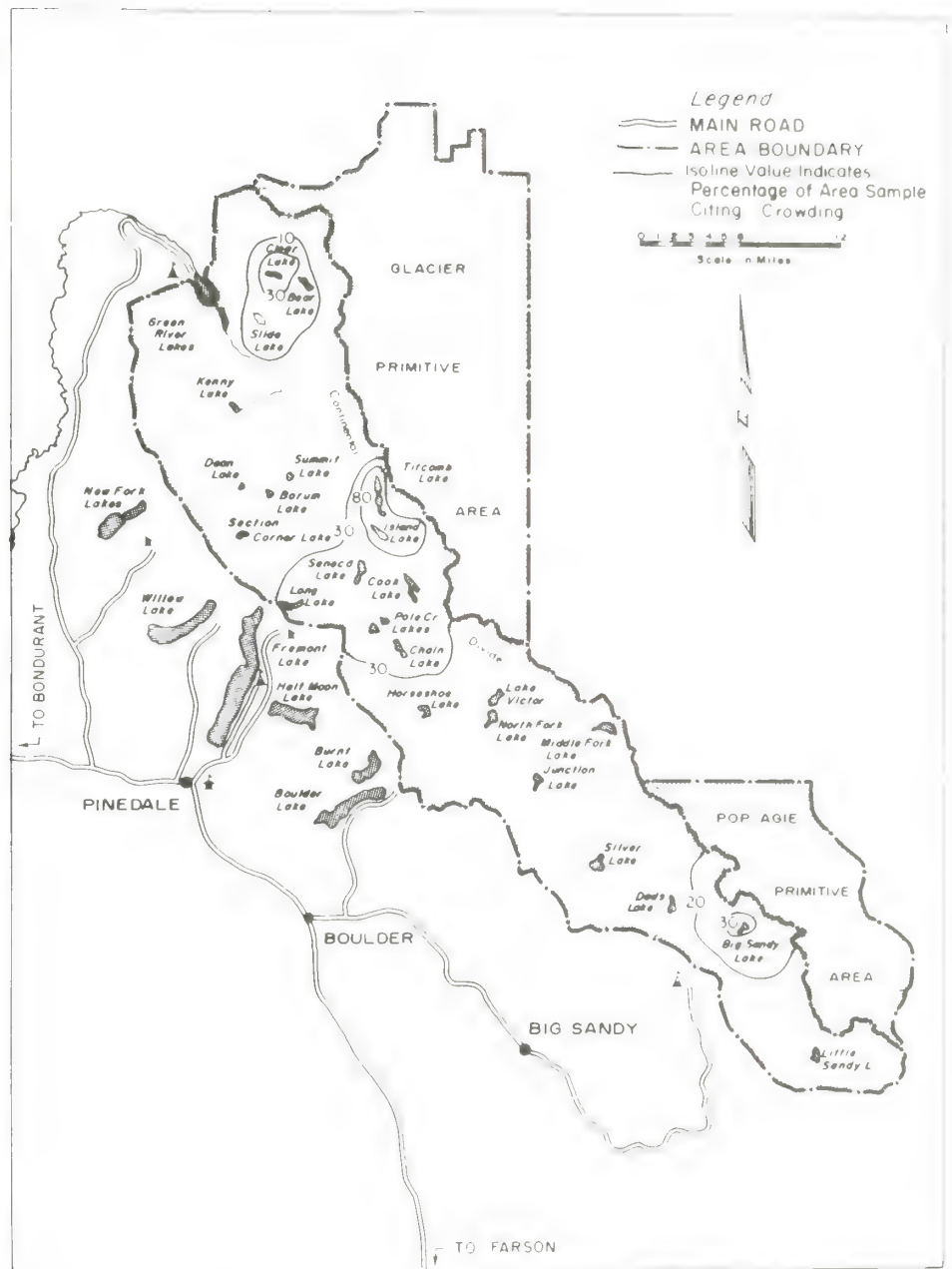
The 383,300-acre Bridger Wilderness is split nearly exactly in half by an oblong zone defined by visitors as severely overused (fig. 9). Island Lake is in the center of this zone which is reached by a well-used trail from Elkheart Park. Considerable day use enters here, destined primarily for Long Lake, about a mile from the end of the road.

Two other areas of overuse lie at opposite ends of the wilderness. The northwest end, with good fishing in the Slide Lake area, coupled with its proximity to the road end at Green River Lake, attracts heavy use. At the southeastern end, similar conditions create a problem of overuse in the Big Sandy Lake area.

Complaints of excessive trail traffic were common in the Bridger, particularly from visitors to the Big Sandy area and those traveling the trail from Elkheart Park to Island and Seneca Lakes. This may be related to encounters between those seeking a wilderness experience as opposed to those primarily interested in fishing at a mountain lake.

There is an extensive amount of grazing by sheep in the Bridger. Allotments have been established to hold numbers of sheep in line with grazing capacity, but it is apparent from our study that sheep are contributing to a serious decline in visitor satisfaction. There are at least three sources of friction: (1) The changes caused by grazing of alpine meadows and its effect upon esthetics; (2) other evidence of the sheep's presence, such as odor, manure, and dust; and (3) their competition with recreational packstock for forage. Sheep grazing is declining, however; personnel of the Bridger Forest indicate over a 50 percent reduction since 1940. Increasing costs of such grazing probably will cause this decline to continue. One visitor commented: "The sheep, of course, lent their noxious presence to an otherwise superb area."

Figure 9.--Zones of crowding within the Bridger Wilderness Area.



Overuse and Crowding in the High Uintas

Visitors identified three major areas in the High Uintas as crowded (fig. 10). This crowding can be attributed to two factors: (1) Clustering of lakes; and (2) relative closeness to access points into the Primitive Area.

About ten percent of the campers in Naturalist Basin and the Brinton Meadows area perceived crowding as a problem; however, this figure rose to 40 percent in the Brown Duck area. In all three areas, these percentages were higher for individual lakes. This reflects what we had noted previously; namely, that the tolerance was low for other users locating near a visitor's campsite. In these areas, most of the visitors indicated they had selected lake areas for overnight campsites.

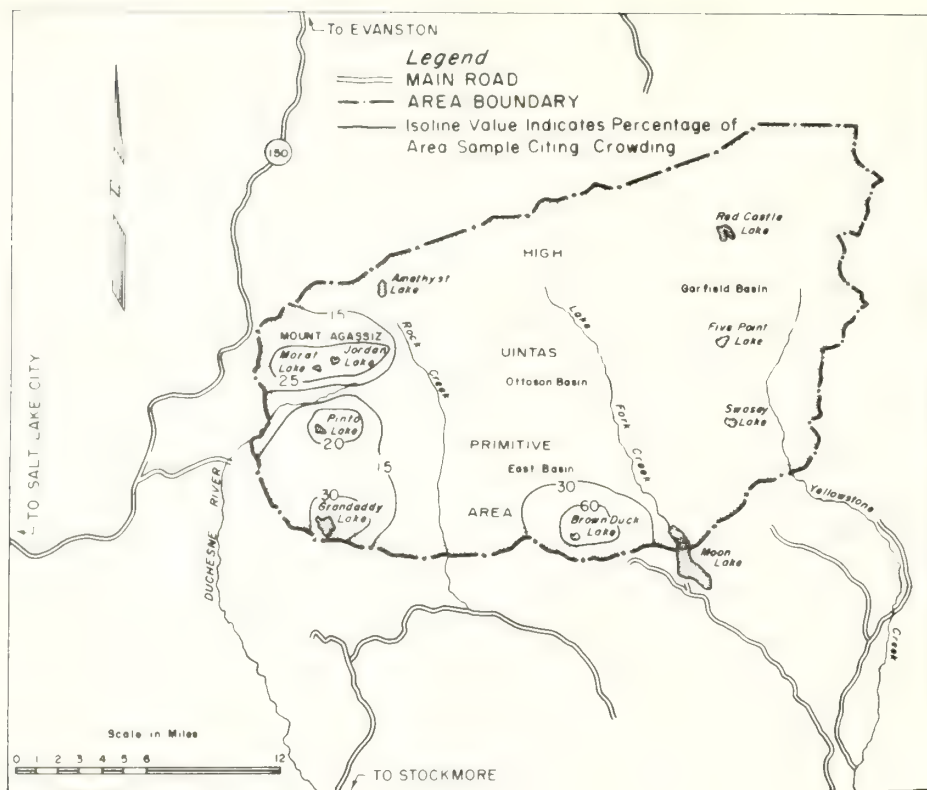


Figure 10.--Zones of crowding within the High Uintas Primitive Area.

Several persons commented that the first few miles of the access trails were crowded, particularly along the Highline trail, but "this was to be expected." This type of response suggests that a person may experience some undesirable element in his immediate environment, but is willing to tolerate it because of the particular setting. It also concurs with one earlier conclusion that users zone wilderness into a "peripheral" area and a "core" area. Expectation of encounters with others is higher in a peripheral area; consequently, visitors appear more willing to accept encounters in such an area than in a core area.

A substantial proportion of the High Uintas does not receive the level or type of use visitors consider as crowded. As suggested earlier, wilderness use is highly skewed in its spatial distribution. The three areas of crowding are all adjacent to the Primitive Area boundary; in the case of Naturalist Basin, a major State highway lies within a few miles of the area. This poor internal distribution of use is a result, in part, of the pattern of development that has taken place outside the Primitive Area boundary. Also, all three areas possess a number of lakes that provide good fishing opportunities coupled with nearness to the road end. The chance for good fishing in an environment still largely unmodified by man makes it especially attractive to outdoorsmen. The level of concern for overuse, however, suggests the very characteristics that make the area attractive may be simultaneously fostering a condition of reduced quality.

MANAGING FOR CARRYING CAPACITY

How to manage wilderness within its carrying capacity has become one of the central issues confronting administrators today (Dana 1957; Clawson and Knetsch 1963). The National Park Service has initiated a limited program of rationing and visitor limitation in three National Parks (Taylor 1972) and the Forest Service has moved to restrict growing use in some southern California wildernesses. The motivation for these seemingly radical actions has been a concern that increasing use threatens the environmental and esthetic qualities of wilderness.

Rationing "across the boards," however, fails to distinguish the disproportionate impact some uses have compared to others on the environmental and esthetic qualities of wilderness. Although it is democratic, it can mislead administrators into thinking that because action has been taken, the problem is being solved. In making the decision to ration use, our concern should be on reducing the impacts of use on wilderness rather than simply restricting use. Hendee,¹⁵ in an unpublished lecture, has described the issue as one of rationing the "environmental expense" of use. Under this concept, one attempts to rank the relative impact of various uses on the wilderness and make decisions regarding rationing or control according to this ranking.

The concept of "rationing environmental expense" fits closely with the concept of "limits of acceptable change." Both draw our attention to specifying sensitive indicators of overuse and provide a rationale for making rationing decisions that avoids arbitrary administrative judgments.

With these concepts in mind, a variety of administrative actions have been defined that would help offset current sources of visitor dissatisfaction. These actions are based upon the data reported herein. The basic objective of each action would be to lessen the "environmental costs" associated with various situations.

Party Size Limitations

The severe impact of large parties on visitor satisfaction and the adverse effect of such on both managers' and users' objectives warrants restrictions on the number of

¹⁵John C. Hendee. Principles of wilderness management. Unpublished lecture given to conservation groups and University classes.



Poor handling of stock not only can result in damage to vegetation and soils, but can also result in deteriorated sites that have little esthetic appeal.

persons and stock. A party size limit of no more than 25 persons appears to be about the largest group possible consistent with protection of the quality of the experience for others such a party might encounter.

Stock numbers also must be controlled. Limiting packstock to about one animal per guest seems desirable. The adoption of some of the new, light camping gear would facilitate this. Initially, this might cost the outfitter more, but his long term costs would probably be reduced because (a) fewer packstock would be needed, thus, fewer wranglers would be required; and (b) greater durability of the newer equipment such as nylon tents

Commercial outfitters operating on National Forest lands are presently regulated by special-use permits in terms of itineraries and number of stock. Such a system provides a convenient framework for wilderness managers to further offset the adverse effects of large parties.

The growing interest in mandatory wilderness registration provides an opportunity to adopt measures designed to minimize the adverse effects of large parties. For example, managers could suggest that itineraries be scheduled to prevent overlap with other large parties. It might be advisable to keep these parties separated by at least one day's travel.

Control of Littering

The presence of litter is a major source of dissatisfaction to all wilderness visitors. There are probably a number of control actions worth consideration. Certainly, the cleanup of residual litter, coupled with a continuing program of cleanup, is important. There should also be improvement in the legal mechanisms to enforce antilitter regulations.

In 1971, the use of noncombustible materials in the BWCA was banned. Tentative reports suggest the program has been highly successful and well received by users. A similar action might be adopted elsewhere; it could do much to halt continuing litter accumulations.

Forest Service regulations regarding litter disposal need to be communicated more effectively. Preliminary results of a survey of wilderness users in the Northern Rocky Mountains indicated that 30 percent thought burying was the proper procedure for disposal of noncombustible trash.

Beyond these measures, concern needs to be directed toward a modification of visitor behavior. Regulations and legal sanctions against littering will probably never be completely satisfactory in contending with the problem. Additional research should be encouraged toward the understanding of how such depreciative behavior could be altered. For example, recent studies in a special interest hiking area and in a dispersed car camping location demonstrate that provision of incentives can yield substantial reductions in litter levels (Clark, Hendee, and Burgess 1972).

Provide Wilderness Users a Greater Basis for Choice

Apparently, present visitors have little information concerning alternative opportunities and attractions that affect their use of wildernesses. Many probably tend to follow familiar routes or routes that are already mapped.

Additional sources of information might be one method of changing use patterns. Information on special attractions, fishing opportunities, scenic hikes, out-of-the-way campsites, available horsefeed, and so forth, could be made available to the users through improved maps and/or guidebooks, or the use of other media such as television, radio, or newspapers.

Publications could have two important functions: (1) They could serve as an important management tool, particularly if it can be demonstrated that patterns of use can be influenced by making this information available to the wilderness visitor; (2) such publications could represent an important means of enhancing the visitor's satisfaction and understanding of the wilderness. The total quality of the experience could be enhanced by providing data concerning the area's diversity as well as information concerning the biological and geological nature of the environment. However, excessive description should be avoided in the writing of such publications so that the visitor would not lose his sense of adventure and discovery. Moreover, there is the potential problem of additional information leading to increased use--in a sense, a counter-productive result of efforts to lessen use impacts. However, this possibility should not serve as the criterion for making a decision whether or not to provide such materials. Rather, if providing people with more complete information leads to use in excess of an area's capacity, then a rational system of regulation rather than the suppression of information should be instituted.

In our study, nearly 20 percent of the visitors were found to be either "neutralists" or "nonpurists;" these persons were probably seeking an experience that could be satisfied in areas managed for a primitive kind of recreation rather than as wilderness. Thus, attention must be turned to developing positive management programs to provide such opportunities as well as techniques to disseminate information regarding these areas to the pertinent audience.

Eliminate Motor Craft in the BWCA

Despite provisions of the Wilderness Act that permit continued use of motor craft, use must be restricted in the BWCA if "outstanding opportunities for solitude" in a



Access roads leading to the wilderness have a major influence on the use within the area. Road construction programs in areas adjacent to wilderness should consider that the last few miles of driving could be a prelude, a slowing down from the conventional.

primitive environment are to be provided. Lucas (1964) noted that elimination of motor craft beyond the second lake from the boundary would greatly increase capacity and his observation, made 10 years ago, seems even more pertinent today.

McCool and Merriam (1970) suggest that restriction of motor craft might not be as vigorously opposed as previously thought. They found between 25 and 35 percent of those persons currently traveling by motor craft would prefer traveling by paddling canoe.

It is paradoxical that the objective of providing a unique opportunity for primitive canoeing and camping is compromised by the presence of motorboats in an area designated as a "Canoe Area." The continued presence of motor craft will only result in an earlier need for restrictions on the number of visitors permitted in the BWCA.

Examine Existing Access to Wilderness Boundaries

Although not specifically investigated, the problems of development adjacent to wilderness aggravated many wilderness management problems. We have tended to regard the wilderness boundary as an effective barrier to potentially adverse impacts resulting from management decisions on surrounding lands outside--particularly in terms of roads developed adjacent to these boundaries. Too often the areal impacts of such roads on wilderness have been underestimated or not considered at all.

In the past, part of this problem stemmed from the lack of definitive policy guidelines regarding wilderness. Management decisions regarding road construction near wilderness areas were often guided by principles more applicable to intensive recreation developments where access for a large number of persons is a prime consideration. However, management objectives for wilderness call for the provision of a special type of opportunity that is difficult if not impossible to achieve under heavy use. The improvement of the Fernberg Road in the BWCA is an example. Records indicate that recreational use was high on lakes adjacent to the road, particularly Fall Lake and Moose Lake. Forest Service officials generally recognized that use was excessive; yet, access was improved to accommodate this heavy traffic. The improvement will only make it easier for additional traffic to move into the area and the use problems on Fall Lake and Moose Lake will be further aggravated.

The following three actions appear available to managers seeking to offset the heavy use conditions that can develop along a wilderness boundary:

1. Transportation plans could eliminate the practice of extending road ends up to the wilderness boundary. Where roads are presently adjacent to the boundary, serious consideration could be given to blocking off the last few miles. If it proves necessary for roads to be built into this area (for example, to harvest timber) these roads could be closed to the public.

2. Where possible, trails branching off from main access routes could be developed to promote a more rapid dispersion of use and consequently, a lowered probability of encountering others. In some areas, this might not be possible because of terrain features.

3. Means of achieving more equitable distribution of use at access points should be investigated, fully recognizing that moving use from one area to another may only relocate the problem rather than eliminate it. However, the highly skewed nature of visitor concentration at access points certainly warrants an effort to effect some redistribution. Such a result could be obtained by developing or improving access to areas presently not utilized. This could include the development of overnight facilities at trail heads or facilities designed especially for horse parties (corrals, stock unloading ramps, and so forth). Another option is to provide better information to visitors regarding alternative access, which could be done using maps or signs. However, such redistribution at access points will have an impact upon levels and patterns of use within wilderness areas.



Fishing is an important aspect of wilderness recreational use. However, much of the fishing that occurs is not wilderness-dependent; that is, its availability is not dependent on the area being wilderness. As a result, conflicts arise between persons seeking just good fishing and persons seeking a wilderness experience.

The issue of achieving more even use distributions in wilderness is a complex one. In some wildernesses, small areas experience severe overuse while the bulk of the remainder is virtually unutilized. Efforts to redistribute use in such areas could provide more users with a more satisfactory wilderness experience by reducing congestion and conflict at local areas. However, there is a trade-off involved in that redistributing use means (1) the ecological effects of use become more widely distributed and (2) areas once trailless now become developed and the opportunity they provided for solitude altered. The decision to attempt to achieve a more even use distribution must recognize this trade-off and will require sensitive judgment on the part of administrators.

Elimination of Structures

All structures that are not necessary for the administration of the area as *wilderness* should be removed at the earliest possible time. The Wilderness Act provides specific guidelines on buildings; our findings suggest strong purists, as well as most other visitors, largely agree with these guidelines. For example, criticism from respondents in our study indicate that excessive campsite developments represent a source of dissatisfaction.

Establish Fish and Game Restrictions

Unquestionably, fishing is an important aspect of wilderness recreational use. The opportunity to fish in a natural setting with usually good success is a powerful appeal to many--particularly when the stream or lake is close to the wilderness boundary. However, this has unfortunate consequences; specifically, it not only increases trail traffic, but it also increases chances that deterioration of the natural surroundings will be accelerated.

Moreover, much of the fishing that takes place in wilderness is not a *wilderness-dependent* type of activity. That is, people fish the lake or stream because of the probability of success and it is only incidental that this location happens to be in wilderness. The fishing would continue even if the area were not a wilderness (assuming roads were not developed). Thus, we find wilderness, a scarce and nonreproducible resource capable of providing a unique and nonsubstitutable kind of recreational experience, often being used as a base for activities, such as fishing, that can be provided relatively easily in other settings. The cost of this situation is growing conflicts between fishermen and wilderness buffs and a potential hastening of the day when restrictions on use will be required.

Much day-use probably could be eliminated by modifications of creel limits. Many States presently have a "10-fish-a-day" or "20-in-possession" limit. Under the terms of the Wilderness Act, fish and game regulations remain under the jurisdiction of the States. State and Federal agencies could cooperate in adjusting creel limits to permit the taking of fish only for food on the wilderness trip itself. Such would discourage use of the wilderness by the day-visitor interested only in fishing, yet still permit fishing as an important aspect of the wilderness trip. Enforcement poses problems, but should not be viewed as insurmountable. Creel limits could be reduced within wildernesses.

Apparently, the hunting situation is quite different. There is probably less of the casual, one day type of use that characterizes fishing. Additionally, big game seasons normally occur in the fall when weather is worsening and the intensities of use in many areas probably do not approach those of the spring and summer fishing period. Fishing use is concentrated along stream and lakeshores, while hunting use is probably more widely dispersed.

Encourage "Off-Season" Use

Overuse and crowding show considerable periodicity. In most of the western wildernesses, a disproportionate amount of the total use occurs during the month of August.

Redistributing use into periods where use levels are presently low would involve an information and education program designed to inform visitors of the advantages of "off-season" travel--e.g., solitude, fall coloring, wildflowers, and wildlife migration. Such information could be disseminated through brochures, personal contact, or various conservation organizations (Brandborg 1963).

A second method would involve working through State fish and game associations. Some temporal redistribution could be gained by manipulating the opening and closing of various seasons. This would be particularly true of hunters. Fall use in some areas could be entirely eliminated by delaying the opening of the big game seasons. Conversely, an early opening would increase the level and duration of use in an area. Staggering seasons might result in a more even distribution of use.

There would also be opportunities to shift use spatially. Where unacceptable resource damage might accompany extended use in some areas, early closing or even total closure to fishing or hunting could be utilized to protect the resource. This would be particularly important where spring or fall rains aggravate potential soil erosion or other physical conditions.

As discussed earlier, any management alternations might lead to increased use, rather than to a better spatial or temporal distribution. Encouraging off-season use might simply result in more use. Any such efforts should recognize this potentiality and provisions made to cope with it.

Zoning¹⁶

Zoning could alleviate resource damage and enhance visitor satisfaction. Opportunities to both spatially and temporally redistribute use would be possible.

Certain areas in many of the wildernesses are subject to considerable resource damage from horses in the early part of the season. As snows melt and spring and early summer rains occur, the chances of excessive resource damage to saturated soils are greatly increased. These areas could be zoned against horses, perhaps for the entire season, or for periods when chances of damage are greatest.

In some areas, or at certain times, there may be sufficient reason to restrict all use. We can apply the "limits of acceptable change" concept discussed earlier to describe such a situation. Research in the BWCA (Ream 1968) has disclosed that presence of visitors on islands is a major factor in nest abandonment by loons (*Gavia immer*). Even low intensities of use by canoeists apparently affect nesting success. Thus, if we judge that preservation of the loon is the major consideration (that is, we say we do not want nesting success to decline at all as a result of recreational use), we have defined the "LAC" and the capacity would be judged as "no use." In this situation, the critical period of nesting is between mid-May and mid-June and no use would be permitted in loon nesting areas. After this time, other criteria, perhaps social considerations, would affect the capacity issue.

¹⁶FSM 2320 notes: "Parts of any wilderness may be designated as management units if they are recognized as having distinctive management situations and needing individual management direction and related coordinating requirements to ensure that the basic objective of maintaining an enduring resource of wilderness is achieved." This differential application of management within wilderness is herein referred to as "zoning."



...the

Closure of Damaged Campsites

Prohibiting use of sites damaged from overuse is an important action in light of the Wilderness Act as well as in terms of its effect upon the wilderness experience. Such has been done in the Bob Marshall; examples could be cited where similar actions should be initiated in other wildernesses.

In some cases, restoration activities might be warranted. Sites where vegetation has been severely disturbed might not recover for a substantial time under natural conditions. Carefully regulated applications of fertilizer, for example, could return the site to its natural condition in a short time. The benefit to be gained from accelerating recovery of the resource would need to be weighed against any potential adverse results.

Campsite closures will need to be complemented by an effort to provide visitors with information regarding which sites are closed as well as alternative camping locations. The institution of mandatory wilderness permits would provide a convenient opportunity for contact with users in order to provide this information (Hendee and Lucas 1973).

Formalizing the Role of Wilderness

Perhaps one of the most significant actions that could be undertaken by administrators to increase capacity is to attempt to promote better public understanding of the objectives of the National Wilderness Preservation System. The manner in which the

preservation objectives mesh with overall resource planning should be shown--particularly, the concept that wilderness represents one type of opportunity along a continuum of environments having varying degrees of human influence. Failure to do so could lead to a growing disparity between public perception of the purposes of wilderness and management objectives and intent.

More effort could be directed at communicating norms of wilderness behavior. I have referred to the many complaints made concerning behavior regarded as inappropriate in the wilderness environment. The difference in behavior should be viewed as reflections of differing tastes, objectives, and motivations rather than as purposeful malicious acts. Thus, rather than expending public funds on programs of questionable efficacy to change people's behavior to conform with values resource managers deem desirable, we should strive to provide opportunities to fulfill these diverse tastes. Through such an effort, one would hope to achieve a distribution of users among the various opportunities that most nearly satisfied their personal motivations and objectives. By achieving such a distribution, one would expect to see the conflicts produced by frictions between varying value systems reduced; e.g., providing alternative opportunities for wilderness canoeists and motorboaters. However, such a program raises other important management implications: (1) It will necessitate positive management efforts to provide the necessary range of diversity; and (2) it will require an aggressive, imaginative effort to provide knowledge of this diversity to potential users. Both of these implications, to date, however, have received little attention.

Restricting the Number of Users

Both the ecological integrity of wilderness and the unique type of recreational opportunity such areas provide are threatened by increasing use pressures. In particular, the recreational experience offered by wilderness is especially sensitive to congestion and related problems such as intergroup conflicts. Beyond what most people would consider fairly low densities of use, the opportunities for solitude are greatly constrained. But formidable questions confront use when we seek to specify such levels or when we attempt to describe the optimal "mix" of uses.

Considerable interest has arisen in developing computer simulation models that would permit managers to forecast when use will exceed an area's carrying capacity. However, as we discussed earlier, there is no single carrying capacity and the most sophisticated forms of analysis will not yield decisions regarding the "right" amount of use that should be permitted. Computer simulation *can* provide managers with a measure of the probable consequences of alternative actions and can describe expected interactions between important variables. But the decision as to the "goodness" or "badness" of the consequences must be a human judgment, based on objectives for the area in question. A current cooperative research effort between the Wilderness Management Research project at Missoula and Resources for the Future, Inc., Washington, D.C., is attempting to develop a model that combines a travel-behavior simulator with data from survey research regarding visitor response to varying levels and types of use (Fisher and Krutilla 1972).

It is perhaps useful to describe some of the underlying assumptions and premises of the model. As was demonstrated in the earlier section on "Use and Satisfaction," there is evidence that the quality of the wilderness experience is diminished as a result of congestion. This diminution of quality shows varying sensitivity under different conditions; e.g., quality declines quickly in the presence of motorboats. Typically, however, increasing intensity of use (and therefore, increased probabilities of encountering others), is associated with declining judgments of satisfaction.¹⁷

The probability of encountering others in a wilderness trip is a function of several variables: (1) Amount of use; (2) length of use season; (3) temporal distribution

¹⁷"Encounters" are not the only way satisfaction is lost on a wilderness trip. However, they do provide us with relatively easily quantifiable measure of a cost of congestion.

of use; (4) method of travel; (5) distribution of use at trail heads; (6) trail system; (7) topography and vegetation, which affect intergroup visibility; and so forth. In the present cooperative investigation, interest has focused on how probabilities of encounter among backpackers and horseback riders are influenced by changing use levels on an existing trail system. This involves the development of a travel-behavior simulator which generates probabilistic distributions of use under varying use levels on the existing trails. Thus, for example, we might discover that under existing use levels, the probability of encountering more than two parties per day is only 1 in 10; when we simulate a 50 percent increase in use, this probability rises to 7 in 10.

As we suggested above, we have data that clearly show that increasing intensities of use result in declining judgments of satisfaction. In the study reported herein, satisfaction was measured only at the *ordinal* level; we are able to say that so many people experienced less enjoyment about meeting an increased level of use, but we cannot say that *aggregate* satisfaction declined by, say, 50 percent when the level of use encountered doubled. In order to make this kind of statement, our measure of satisfaction would need to be at the *interval* level; the distance between any two judgments of satisfaction would need to be known.

If we were able to obtain aggregate measures of satisfaction we would then be able to estimate the trade-offs involved in the decision to allow use to increase. Is the added satisfaction (utility) gained by allowing additional visitors to enter the system offset by the loss in satisfaction experienced by other visitors because the additional use results in a significant increase in the probability of encounters? That is to say, if we allow use to increase by some margin, does the gain in satisfaction (utility) experienced by the newcomers offset the loss in satisfaction by current users that results from the increased congestion?

Some severe methodological problems confront us in regard to the development of this model. Obtaining realistic interval measures of satisfaction is one. A technique currently being utilized is to request visitors to define how a "100 percent" satisfactory experience might be characterized and to relate this judgment to specific hypothetical situations (e.g., a 3-day trip where you encountered 15 backpacking parties). From this, judgments that a situation would provide, for example, a "50 percent of full satisfaction" experience are obtained.

The situation is further confounded because multiple satisfactions are derived from the wilderness experience and the basis on which judgments of degree of satisfaction are made thus shifts from individual to individual. Basically, it is the problem of interpersonal utility. For some persons, the dimensions of solitude are the most critical to their satisfaction. For others, it might variously be the challenge of primitive camping, observing the pristine environment, or the development of close intragroup bonds. Satisfactions derived from these various sources are not necessarily related or additive. However, we are currently treating satisfaction as a unidimensional concept because of our inability to distinguish how these dimensions vary among users.

It is important to understand that the model outlined above, or any other model for that matter, will not make difficult rationing decisions nor will it provide the standards for which we manage wilderness. These are the responsibility of the wilderness administrator and the exercise of these responsibilities calls for a mixture of judgment, sensitivity, and awareness of existing information on the part of administrators. Certainly, the availability of improved data and sophisticated techniques for predicting consequences of alternative actions will upgrade the quality of decision making by reducing uncertainty. For example, the model we describe would yield a probabilistic description of what trade-offs are involved with alternative courses of action, before it is necessary to make a decision that might have irreversible implications. However, we will always face situations where decisions must be made, but when little or no "hard" data exist. In these situations, the role of the perceptive, sensitive wilderness administrator will be crucial. In particular, his ability to monitor, evaluate, and revise, as necessary, management programs will be the major way in which operational guidelines designed to preserve wilderness quality will evolve.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

Boise, Idaho
Bozeman, Montana (in cooperation with Montana State University)
Logan, Utah (in cooperation with Utah State University)
Missoula, Montana (in cooperation with University of Montana)
Moscow, Idaho (in cooperation with the University of Idaho)
Provo, Utah (in cooperation with Brigham Young University)
Reno, Nevada (in cooperation with the University of Nevada)

PHOTOS

Outer cover: *The Boundary Waters Canoe Area in northern Minnesota is the only large water-oriented unit of the National Wilderness Preservation System. It is also the only designated wilderness in the midwest.*

Inner front cover: *Squaretop Mountain, standing above Green River Lakes, greets visitors entering from the northwest end of the Bridger Wilderness.*

Inner back cover: *The Chinese Wall in the Bob Marshall Wilderness is a major scenic attraction.*

SOURCES OF VISITOR DISSATISFACTION MIGHT BE OFFSET BY VISITORS EITHER HEIGHTENING OR REDUCING SENSITIVITY. THIS SUGGESTS THAT EFFORTS TO FORMULATE A MEASURE OF CARRYING CAPACITY MIGHT BE VALID ONLY AT ONE POINT IN SPACE OR TIME. NEVERTHELESS, WHEN THOSE PERSONS DESCRIBED AS STRONG PURISTS ARE CONSIDERED, IT IS CLEAR THAT CERTAIN NORMS AND VALUES ARE SHARED OVER THE FOUR AREAS STUDIED.

A CHANGING CLIENTELE MIGHT BE RESPONSIBLE FOR APPARENT CHANGES IN ATTITUDES ABOUT CAPACITY. AS THE CHARACTER OF AN AREA CHANGES, EITHER BECAUSE OF SHIFTS IN GEOLOGY OR BECAUSE OF MANAGERIAL PROGRAMS, PERSONS ESPECIALLY SENSITIVE TO THESE CHANGES MIGHT "DROP OUT", USE DOES NOT DECLINE, HOWEVER, AS OTHER PERSONS, DRAWN TO THE AREA PERHAPS BECAUSE OF THE VERY CHANGES THAT LEAD THE FORMER USERS TO LEAVE, ENTER THE AREA. THE PROCESS OF "DISPLACEMENT" HAS NOT BEEN CLEARLY DOCUMENTED, BUT IT HAS SIGNIFICANT IMPLICATIONS FOR THE ESTABLISHMENT OF CAPACITY GUIDELINES.

MOST VISITORS INDICATE THE QUALITY OF THE WILDERNESS VISIT BEGINS TO DIMINISH BEYOND ABOUT TWO ENCOUNTERS PER DAY. THE MAJOR EXCEPTION TO THE INVOLVES ENCOUNTERS WITH MOTOR CRAFT IN THE BWCA. IN THE CASE, MOST VISITORS INDICATE ONE ENCOUNTER IS EXCESSIVE.

THERE IS A FAIRLY SIMILARITY AMONG THE FOUR AREAS REGARDING THE ENCOUNTERS AND THEIR EFFECT ON SATISFACTION. THE RESULTS INDICATE DESPITE DIFFERENCES IN AREA CHARACTERISTICS, AND TYPE AND AMOUNT OF RECREATIONAL USE, A SHARED NORM EXISTED REGARDING THE ENCOUNTERS.

USERS MENTALLY ZONE WILDERNESS AT A MACRO-SCALE, RECOGNIZING AT LEAST ONE "PRIMITIVE" AREA (PORTAL ZONE) AND A "CORE" REGION FOR MINIMUM ZONE. ATTITUDES ABOUT MEETING OTHER GROUPS DIFFER BETWEEN THE ZONES, WITH CORE VISITORS MORE LIKELY TO EMPHATICALLY REJECT THEM IN THE PORTAL ZONE.

SOLITUDE AND SEPARATION FROM INTERPRETED ZONES AT THE CAMP SITE IS AN AMERICAN IDEAL. VISITORS WILL ENJOY "STAYING" IN THE CAMP, BUT VISITORS WILL ALSO ENJOY THE OPPORTUNITY TO CAMP ALONE. OF THESE MORE SO IN AN AMERICAN CAMP. NORMS OF THE AREA'S SOCIAL CARRYING CAPACITY.

THE CAMPSITE APPEARS TO OFFER THE VISITOR AN OPPORTUNITY TO STRENGTHEN INTERACTIONS IN A MANNER DIFFICULT TO ACHIEVE IN AN INCREASINGLY DEPERSONALIZED WORLD.

EVIDENCE OF VISITOR MENTAL ZONING, SUCH AS THE CAMP SITE, IS A MAJOR SOURCE OF VISITOR SATISFACTION. IT APPEARS THAT CERTAIN WELL-ESTABLISHED NORMS REGARDING APPROPRIATE WILDERNESS BEHAVIOR EXIST AND THAT VIOLATION OF THESE NORMS HAS AN UNDESIRABLY MAJOR IMPACT ON THE QUALITY OF THE EXPERIENCE FOR OTHER VISITORS.



Visitor Attitudes About Use Regulation

- NO RATIONING TECHNIQUE WAS FAVORED BY A MAJORITY OF USERS. HOWEVER, THERE WERE CLEAR DIFFERENCES IN THE LEVEL OF ACCEPTABILITY AMONG VARIOUS TECHNIQUES, WITH A MAIL RESERVATION SYSTEM THE MOST ACCEPTABLE, AND ASSIGNING TRIP ROUTES, THE LEAST.
- APPROXIMATELY 20 PERCENT OF THE RESPONDENTS WERE NEUTRAL ON THE ISSUE OF RATIONING. A SENSITIVE, INTELLIGENT APPROACH TO INFORMING USERS OF THE NEED FOR RATIONING SHOULD BE PUT FORTH TO GAIN THE SUPPORT OF THIS UNCOMMITTED GROUP.
- INDIRECT RATIONING TECHNIQUES, INVOLVING MEASURES SUCH AS MINIMAL TRAIL AND SIGN SYSTEMS, REPRESENT MORE ACCEPTABLE METHODS OF USE CONTROL THAN PERMITS OR FEES.
- MANAGERIAL ACTIONS THAT INVOLVE DIRECT OR "HEAVY HANDED" MODIFICATIONS OF WILDERNESS ARE REJECTED BY MOST VISITORS. THOSE ACTIONS THAT INFLUENCE USE IN A MORE SUBTLE, DISCRETE FASHION, SUCH AS MAPS, ARE SEEN AS MORE FAVORABLE.
- THE BELIEF THAT WILDERNESS VISITORS ARE PARTICULARLY CONVENIENCE-ORIENTED STEMS FROM A MISPERCEPTION OF USER DESIRES RATHER THAN FROM AN ACCURATE ASSESSMENT OF THE USER'S PREFERENCE.

The Relationship of Recreation Use to Capacity

- FOR MOST VISITORS, CROWDING DOES NOT REPRESENT A PROBLEM. HOWEVER, ABOUT ONE OUT OF FOUR PERSONS SAMPLED DID CITE CROWDING AS A PROBLEM; OVER ONE-THIRD OF THE STRONG PURISTS SO RESPONDED.
- ALL FOUR STUDY AREAS HAD LOCATIONS DEFINED BY VISITORS AS CROWDED. GENERALLY, THESE ZONES OF CROWDING WERE RELATED TO WELL-DEVELOPED ACCESS AND THE PRESENCE OF ATTRACTIONS, SUCH AS FISHING.
- VISITOR DEFINITIONS OF CROWDING INCLUDED NOT ONLY EXCESSIVE USE LEVELS, BUT CONFLICTS WITH OTHER GROUPS (PADDLING CANOE AND MOTORBOAT CONFLICTS, FOR EXAMPLE), THE INABILITY TO FIND ISOLATED CAMPSITES, AND LITTER AND BEAT-UP CAMPSITES.
- THERE IS EVIDENCE TO SUGGEST THAT VISITORS ESTABLISH PERSONAL HIERARCHIES IN EVALUATING ONE DIMENSION OF CARRYING CAPACITY WITH ANOTHER. FOR EXAMPLE, THE PRESENCE OF LITTER APPEARS TO REPRESENT A MORE SERIOUS SOURCE OF DISSATISFACTION THAN DOES ENCOUNTERING EXCESSIVE USE. GIVEN THE CONSTRAINTS ON BUDGET AND MANPOWER WILDERNESS MANAGEMENT AGENCIES WILL GENERALLY BE CONFRONTED WITH, THIS HIERARCHY HAS IMPORTANT IMPLICATIONS FOR THE ESTABLISHMENT OF MANAGEMENT PRIORITIES.



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James L. Clayton and Chester E. Jensen

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Robert W. Harris, Director

THE AUTHORS

JAMES L. CLAYTON has served as Research Soil Scientist with the Intermountain Station since 1967. He received his B.S. and M.S. degrees in soil science from the University of California at Berkeley.

CHESTER E. JENSEN is Principal Statistician for the Intermountain Forest and Range Experiment Station. Previously, he held the same position at the Northeastern and Central States Forest Experiment Stations. Mr. Jensen, who holds a master of forestry degree from Michigan State University, received his training in graduate statistics at Iowa State University.

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ABSTRACT

Volumetric water retention at 1/3 and 15 bars was evaluated for strength of relation to the interacting effects of percent organic matter, percent fines (<50 μ m diameter) and soil bulk density. Samples used in the models were restricted to soils formed from granitic parent materials from the Idaho Batholith.

These soils are unique in that they are coarse-textured and have a broad range of organic matter content. Where a broad range of textures exists, texture (aside from pore size distribution) has often been found to be the single variable most useful in predicting retention. Perhaps by reason of its more limited range (particularly in the clay fraction), texture appeared to have only a secondary effect in the Batholith soils. In contrast, retention was strongly affected by organic matter in the coarse-textured soils here, possibly because of the broad organic matter range and the enhanced potential for organic matter to exert its retention effects. Organic matter alone explains 57 percent of the variance in water retention at 1/3 bar, and 62 percent at 15 bars tension. Incorporating the interacting effects of the remaining two variables explains an additional 17 percent of the variance in water retention at 1/3 bar, and an additional 11 percent at 15 bars.

Tables and equations for the two retention models are presented in the Appendix. The final models were subsequently adjusted by least squares to two new data sets of geographically diverse soils from the Idaho Batholith. The adjusted retention models operate well for predicting water retention at both energy levels. The value of the models is discussed in light of these findings.

INTRODUCTION

Knowledge of the water retention properties of soils is an important facet of the hydrologic data necessary for wise management of forested lands. Management decisions that are based on soil water retention data include: types and expected rates of timber regeneration; potential for erosion and sediment production; changes in water yields following vegetative manipulation; design and location of roads; and a myriad of ecological factors.

Land managers have become increasingly aware of the importance of hydrologic inputs to forest land management in the Idaho Batholith in the last decade as a result of the contrasting values of a timber resource, fishery resource, and the inherent high erosion potential of the Batholith soils (Bethlahmy and Kidd 1966; Gonsior and Gardner 1971; Haupt and Kidd 1965; Megahan and Kidd 1972a and 1972b).

We have attempted in this study to provide a more complete understanding of the interacting effects of percent soil organic matter (OM), bulk density (ρ_b), and percent fines (diameter $<50\mu\text{m}$, F) on water retention. The water retention models developed appear to have regional applicability throughout the Idaho Batholith.

The prediction of soil water storage has practical value only when either the parameters used for this prediction are more easily determined than water retention determined by conventional laboratory techniques, or the soil parameters other than water retention are available. Experienced field soil scientists can make reasonably accurate estimates of texture, organic matter content, and bulk density (Visser 1966), particularly after some training and familiarity with the soils involved.

The coarse nature of the soils (textures are predominantly loamy coarse sands or coarse sandy loams), and the relatively high organic matter content appear to preclude use of existing methods of estimating soil water storage (Smith 1944; Shockley 1955; Broadfoot and Burke 1958; Carlson and others 1956; Stone and Garrison 1940). For this reason another approach to water retention prediction seemed desirable for Batholith soils.

The two energy levels for water retention used in developing the retention models were chosen somewhat arbitrarily. Retention at 15 bars is frequently used as an estimation of the permanent wilting point of a soil. This concept probably has little value in the Batholith except for grasses and forbs. The roots of many shrubs and trees follow fracture lines or penetrate the matrix of highly weathered bedrock and can be found at great depths (40 to 50 feet); presumably they obtain water at these depths after the overlying "soil" has reached the actual wilting point for the species involved. However, the retention at 15 bars is useful and necessary in classifying the moisture regime of soils as specified by the National Cooperative Soil Survey (1970).

Retention at $1/3$ bar has been used frequently for estimating field capacity. In coarse-textured soils, $1/3$ bar is usually considered too high an energy level of water retention (too low a water volume) for this estimation. However, there is no unanimity of opinion among soil scientists as to a better figure; 0.10 bar, 0.061 bar (60 cm.), and 0.05 bar water tension have all been proposed, and can be found in the existing literature. Petersen and others (1971) support utilizing $1/3$ bar measurements, at least until some other value on the moisture characteristic curve becomes widely utilized. Because of the widespread use of $1/3$ bar, the authors concur. The primary intent of this paper is to develop models relating retention to OM, F, and θ_b at two commonly used energy levels.

Because of the rooting nature of plants growing in the Idaho Batholith, the authors make no implication that the difference between 15 bars and $1/3$ bar is the available water.

METHODS

Forty-seven soil samples were collected for laboratory analysis from 28 sites in the southwestern portion of the Idaho Batholith in seven forested experimental watersheds, that are tributaries of the Middle Fork of the Payette River. Elevations range from 1,200 to 2,200 m. on these watersheds, and a large variety of soil families, typical of the southern Batholith, can be sampled here. Great Soil Groups include both Lithic and Entic Cryoborolls and Cryopsamments, and Typic Cryorthents. Families are generally shallow, sandy-skeletal, mixed or coarse-loamy mixed. A-C profiles over weathered quartz monzonite bedrock predominate.

The 47 soil samples used in deriving the original models include A11, A12, AC, and C horizons. No B horizons were present at the 28 sampling sites. Samples were oven-dried at 105° C. and then put through a 2-mm. sieve. Textures were run on the less than 2 mm. fraction by the hydrometer method of Day (1965). Percent fines (silt plus clay) is presented as percent by weight of the <2 mm. fraction. Organic matter analyses were made in a carbon combustion furnace in an oxygen stream, and determined by weight loss. Although this method overestimates organic matter (OM) slightly by dehydration of clays it was found to be more reproducible than wet oxidation methods, probably because of the coarse nature of organic material in the surface horizons. Bulk density samples were taken in the field by use of a 5.71 cm. diameter soil core sampler. Water retention at 15 bars was run on a pressure membrane apparatus, and at 1/3 bar in a porous-plate pressure device. Samples run were from the <2 mm. fraction. Results are expressed on a percent by volume basis. Experience has shown that no attempt at re-packing these loose, weakly aggregated soils best simulates the original bulk density (personal communication with Delon Hampton, Howard Univ. 1971). The change in pore size distribution might be quite drastic using disturbed samples, so we attempted pressure plate analyses of water retention on undisturbed core samples. However, reproducibility was poor, probably because of inadequate contact between the soil and pressure plate. For this reason, we resorted to the use of disturbed samples. This objection is probably small at 15 bars because most water is held by adsorption on particle surfaces. This may be the case for much of the water at 1/3 bar in very coarse soils.

The soil information thus derived for the samples was then subjected to analysis. Preliminary scanning of alternative two- to four-dimensional data plots resulted in the isolation of three independent variables deemed worthy of inclusion in the final models: percent organic matter, percent fines (F) which is equivalent to 100 minus the percent sand, and bulk density (ρ_b).

Expectation and Data Trends

Expected curves for water retention represent our attempts at describing the theoretical relationships between water retention and independent variables, the latter being allowed to vary within prescribed limits. These curves are presented here (figs. 1, 2, and 3) for the three independent variables included in the final models.

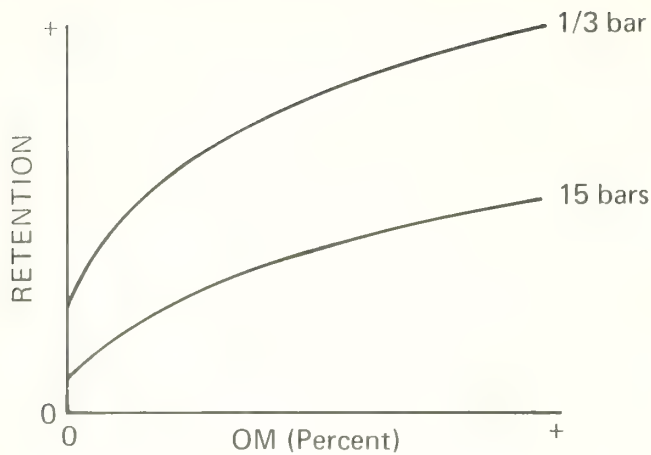


Figure 1.--Expectation for water retention as a function of percent OM.

Our initial expectation was for a linear increase in retention with increasing OM values; however, the data strongly indicated the diminishing increase in retention with increasing OM as shown in figure 1. The curvilinear relation has a positive intercept at OM = 0; this value is equal to the matric potential of a polydispersed system of lithic particles having a pore size distribution that would hypothetically be formed for a coarse-textured mineral soil. The amount of increase in water retention diminishes as OM increases, particularly beyond about 8 percent OM. A possible explanation is that initial increments of OM tend to coat coarse lithic particles and the interstices of large pores, maintaining the single grain structure and not altering pore size distribution. However, at higher OM levels, added increments of OM tend to bind the coarse particles forming a weak crumb structure (Emerson 1959). This would change the pore size distribution, and could result in a higher percentage of large pores. This effect on retention should be more evident at the lower energy level (1/3 bar) since most retention at 15 bars is by adsorptive (surface active) phenomena. Again the data support this. The retention at 15 bars over OM is more nearly linear than it is at 1/3 bar tension.

The expectation for water retention as a function of percent fines (F) (fig. 2) follows essentially the same line of reasoning as retention over OM (fig. 1). Again there is a positive intercept at F = 0, equal to the matric potential of a polydispersed soil in which all particles are greater than 50 μ m in diameter. Initial increments of

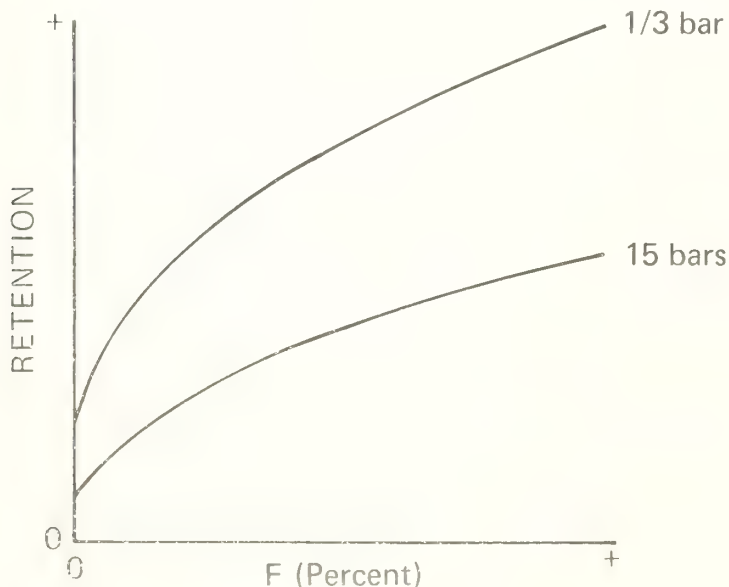
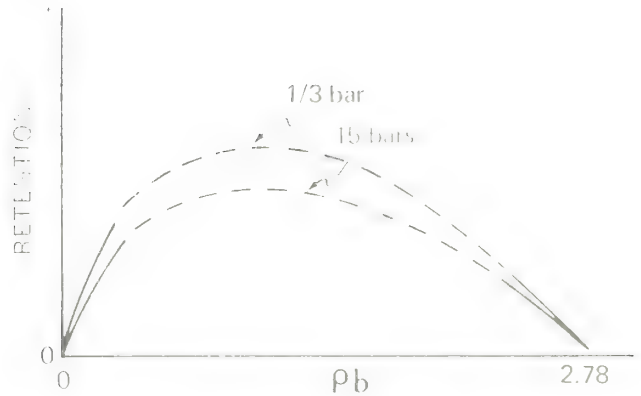


Figure 2.--Expectation for water retention as a function of percent F.

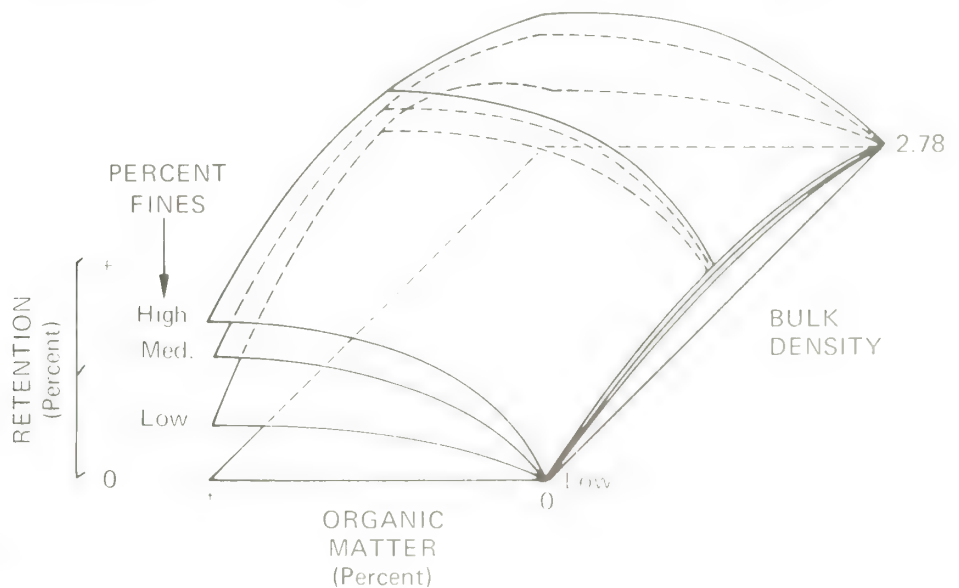
for water retention
as a function of ρ_b .



fine particles occupy large pores, increase the specific surface (and consequently bulk density) and tend to form smaller pores at higher F-levels. Added increments of fines begin to favor a weak crumb structure due to interparticle binding, formation of larger pores, and a decrease in bulk density. The data suggest this phenomenon has a strong effect in the range $F = 20$ to 30 percent by weight.

The expectation for retention over bulk density (ρ_b) poses an interesting problem. Logically, at $\rho_b = 0$ and $\rho_b = \rho_s$ (where ρ_s is solid phase density; approximately 2.78 for our parent materials), porosity and therefore retention is 0 . Retention therefore has two minima and is assumed to have one maximum at some intermediate value (fig. 3). The value of ρ_b where this assumed maximum occurs is a function of the pore size distribution in a polydispersed soil system. The total porosity, E , approaches a maximum where ρ_b approaches zero, but this sheds no light on maximum retention at energy levels (tensions) greater than zero (where zero is saturation percentage). The increase in retention from very low ρ_b values to this maximum is probably attributable to increased specific surface. Interparticle binding by OM or F to form a weak crumb structure diminishes this effect, as previously pointed out.

Changes in the foregoing main effects were expected to occur as the three soil factors interacted and the combined expectation would be as shown in figure 4. Actual data points would be distributed over the ranges of the soil factors in a pattern



relations between
water retention,
organic matter,
bulk density, and
percent fines.

roughly dictated by the correlations between them. Soils with high ρ_b , F, and OM, for example, would not occur. Extension of expectation over these areas is simply a sacrifice to ease of graphic display. A tendency toward convergence of surfaces for all levels of percent fines (F) was expected to occur with decreasing organic matter (OM). With increasing OM and when approaching extremes of bulk density (ρ_b), the suppressive effects of decreasing F on retention were expected to be accentuated.

Model Development

The position of the data array in the expected model and a more precise estimate of the nature of the interaction was next ascertained. Expected retention trends over OM were fitted to the plotted data points by approximate least deviations (for both 1/3 and 15 bars), for two or three F-strata, within each of three ρ_b -strata (see fig. 5).

It was apparent from these data trends that the data lay in the right front quarter of the expected surfaces and were fairly well distributed over low to medium F with only a few high F-values being present. Furthermore, the expected interactions appeared to exist; thus, our next effort was directed at generating a suitably accurate interaction descriptor. Using such a model, we hoped to minimize curve form bias likely to be associated with the application of less sensitive transformations.

The curves over OM were characterized using algebraic forms identified with Matcha-curves-1 and -2 (Jensen and Homeyer 1970 and 1971). Differences in these functions (intercepts, maxima, and degree of curvature), smoothed in accord with expectation, were then expressed as appropriate Matchacurve functions of ρ_b and F to arrive at an algebraic approximation of the four-dimensional relation. And finally, the algebraic function was refitted to the original data points by least squares, using a simple linear model having zero intercept.

The complexity of the final descriptors probably will appear objectionable in our old frame of reference where the lack of available computers necessitated descriptor simplicity. This is no longer true, and where complex algebra was required to describe particular main effects and interactions in the model here, we were not reluctant to use it. The descriptors herein were developed over a period of 1 week and final scaling passes in the computer were extremely short and inexpensive.

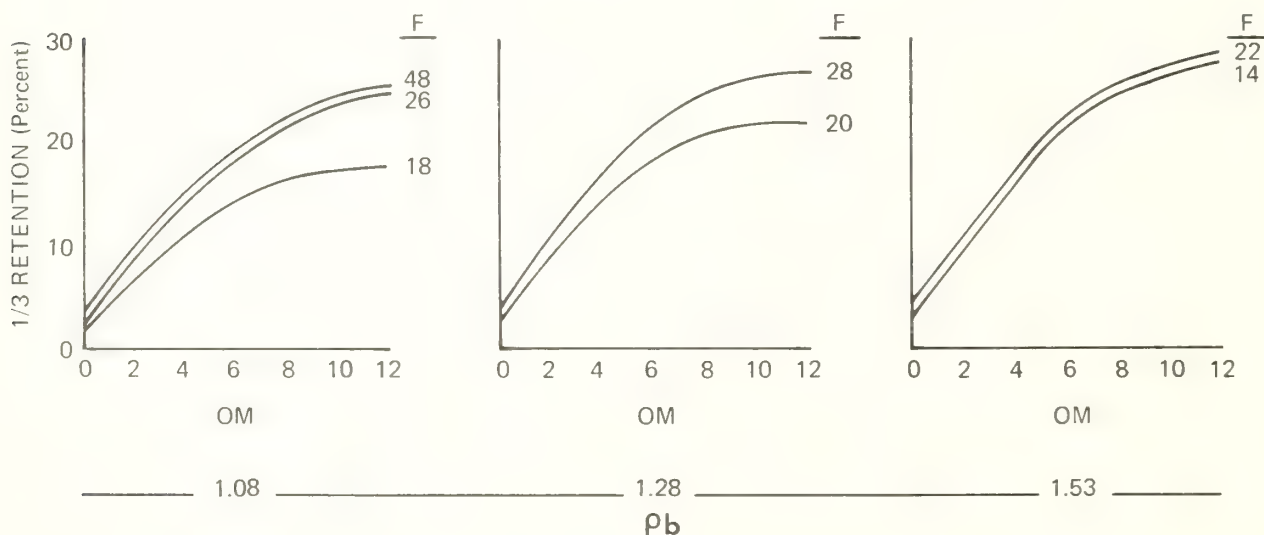


Figure 5.--Expected trends fitted to the data.

RESULTS

Description of the Models

Evaluations of the dependent and independent variables show the means, standard deviations, and ranges for the data used in developing the two water retention models (table 1). The water retention values appear typical for coarse-textured soils. Values published by Broadfoot and Burke (1958, p. 5) can be compared by dividing Batholith soil values by the mean ρ_b value to express retention on a weight basis. The retentions at both energy levels fall between their published values for loamy sand and sandy loam textures. A similar comparison of bulk densities by textural classes can be made with Broadfoot and Burke's data (1958, p. 13) and shows our bulk densities to be similar.

The water retention surfaces incorporating the effects of all independent variables for 1/3 bar and 15 bars tension are presented in figures 6 and 7, along with the indices of determination (R^2), and the standard errors of estimate ($s_{y \cdot x}$). The equations for these models are specified in the Appendix.

Basically these surfaces fit expectation and can be described as follows:

The most significant feature of the 1/3-bar model is that retention increases strongly (15 to 20 percent) as OM increases from 0 to 8 or 10 percent, regardless of ρ_b and F values. At low OM, only small to modest positive effects can be seen over ρ_b and F. And, at high OM, the expected interaction materializes except that the left front third of the figure has been arbitrarily brought to a lower asymptote for each F-level. Data are either scant or absent there. A sharp retention increase in the range $1.3 < \rho_b < 1.5$ occurs in the lower range of F, 10 to 20 percent.

Table 1. *Univariate descriptions of the data.* (N = 47 for all variables)

Item	Mean	Standard deviation	Lowest	Highest	Range
1/3 atm. Pv	15.11	4.14	6.5	27.0	20.5
15 atm. Pv	6.20	1.73	3.7	11.1	7.4
% OM	4.26	1.97	1.6	11.7	10.1
% F	22.80	8.46	7.4	53.0	45.6
Bulk density g/cc	1.30	.19	.94	1.7	.76

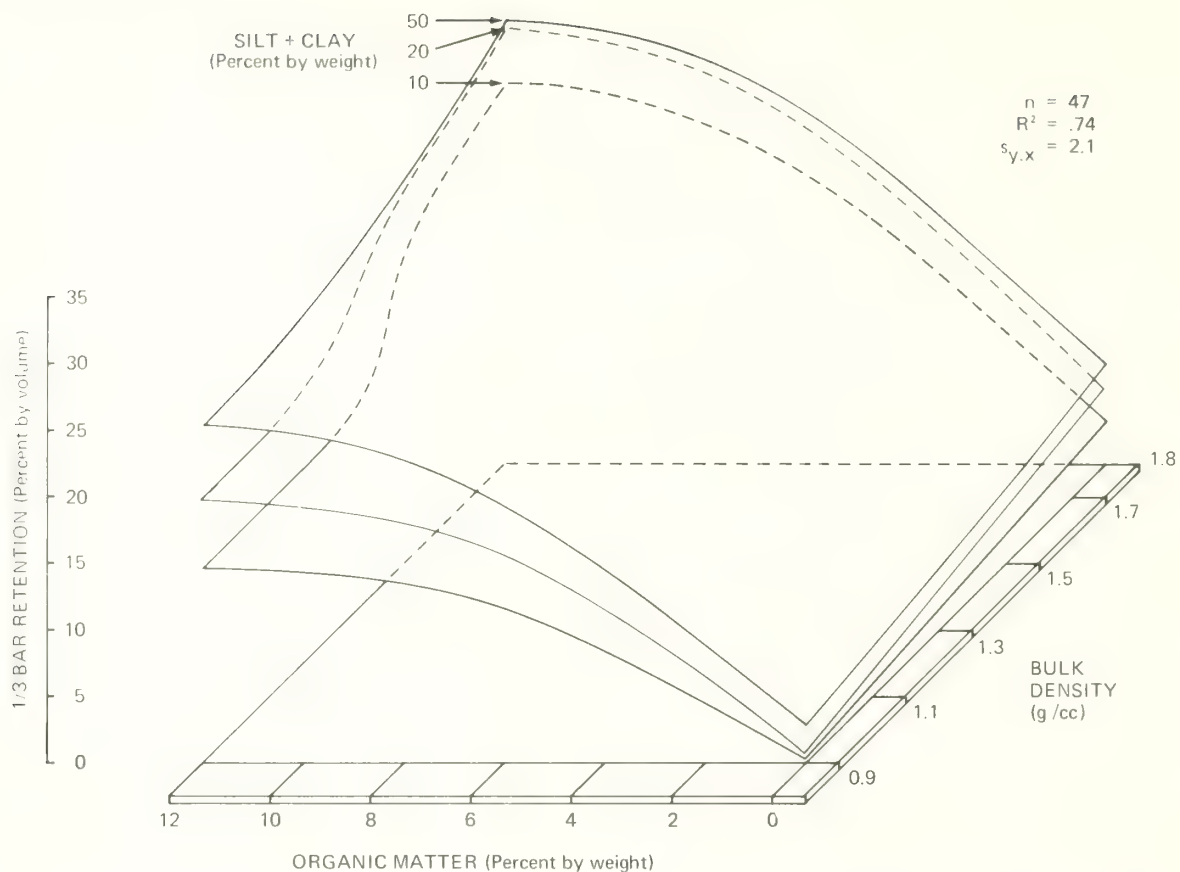


Figure 6.--Water retention at 1/3 bar as a function of percent OM, percent F, and ρ_b .

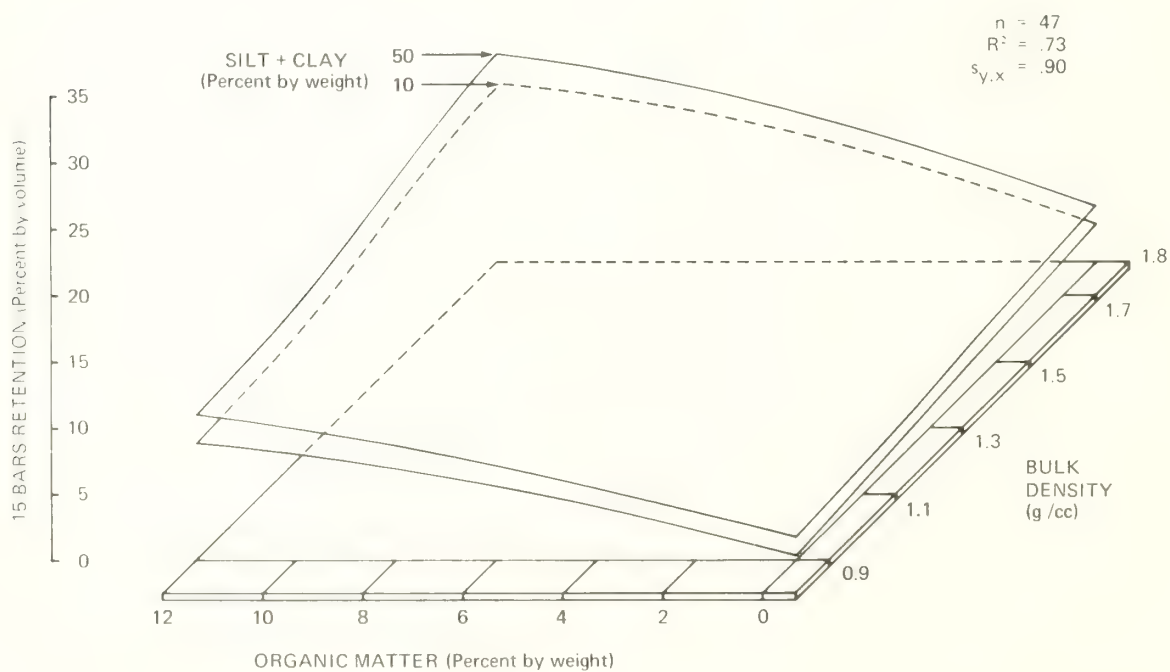


Figure 7.--Water retention at 15 bars as a function of percent OM, percent F, and ρ_b .

There are areas on the surface of figures 6 and 7 showing retention values that are logically impossible, and there are areas wherein there are no real data values. An example is the point on the high F surface of the 1/3 bar model where OM = 12 and $\rho_b = 1.8$. The predicted retention is approximately 33 percent by volume. This is approximately the volume of the total pore space. We do not want to promote the concept that saturation percent is equal to 1/3 bar percent for the above array of independent variables. The tables presented in the Appendix show dashed lines instead of retention values where the model is not deemed applicable.

Basically, the same responses in water retention at 1/3 bar are found at 15 bars tension. One major difference is the lack of sharp change in retention in the middle of the ρ_b range for high OM values and low F values. This indicates that the distinct change at these values noted in the 1/3 bar model may be due to a structural binding of lithic and organic particles to form voids that drain at tensions greater than 1/3 bar, but less than 15 bars. This effect is diminished as percent F increases in the 1/3 bar model. This may indicate that higher fines either mask the effect, or change the structural interaction of OM and lithic material.

At 15 bars tension, organic matter is again the independent variable that most influences water retention. At all OM levels, retention increases with increasing values of both ρ_b and F.

Model Performance

The two retention models were developed from soil samples of a very localized area within the Batholith. How applicable these models might have been to alternative areas was unknown, but some insight was provided by an evaluation of model performance for two additional sets of soil samples from new and geographically diverse areas of the Batholith. Univariate data descriptions for the new data sets appear in tables 2 and 3.

Evaluation of the scale and form of the original models was made possible by first adjusting these models to the new data sets by least squares, in a simple linear model forced through the origin: adjusted retention = b (model retention, M); Y_i = new retention values; and, $b = \sum M_i Y_i / \sum M_i^2$.

The b-value simply shrinks or stretches the original model to fit the new data set without changing the specified form and provides a basis for judging adequacy of the original model scale. A b-value of 1.000 represents a perfect scaling match between model and data set and as may be seen in table 4, the b's ranged from 0.909 to 1.065 for the new data sets; i.e., the original model scales ranged from about 9-percent high to 6-percent low. In a larger array of check data sets, we might reasonably expect an even larger range of corrections, perhaps ± 15 percent. Users of prediction tables 5 and 6, Appendix, should be aware of the magnitude of this potential scaling error for the *unadjusted* models, but users should also realize that the models can be *adjusted* to soil data for any¹ area as they were above for the check data sets, thus removing scaling bias of the models for new areas.

Some idea of the applicability of the *interaction form* for the new data sets is provided by an evaluation of departures of actual retention values from the corresponding ones given by the models adjusted to each new data set (fig. 8, table 4).

¹Again, the authors advise that application of the original models be limited to areas having similar soils and due consideration be given to the need for scaling to the new soils (p. 9, par. 7). Extrapolation to soils having widely differing physical properties should only be attempted after laboratory confirmation of both the form and scale of the models.

Table 2.--Univariate data descriptions for new data set 1;
N = 24 at 15 bars, N = 21 at 1/3 bar

Item	Mean		Standard deviation		Lowest	Highest	Range
	N = 24	N = 21	N = 24	N = 21			
1/3 bar	--	16.00	--	4.30	8.0	25.2	17.2
15 bars	6.70	--	2.07	--	3.2	9.9	6.7
% OM	4.17	4.44	1.86	1.82	1.6	8.6	7.0
% F	19.97	21.30	6.85	7.64	10.0	36.7	26.7
ρb	1.34	1.38	.15	.15	1.13	1.73	.60

Table 3.--Univariate data descriptions for new data
set 2; N = 15

Item	Mean	Standard Deviation	Lowest	Highest	Range
1/3 bar	16.71	4.38	9.4	23.6	14.2
15 bars	6.65	2.12	3.1	11.2	8.1
% OM	5.00	2.21	1.3	9.3	8.0
% F	34.10	9.76	23.0	55.0	32.0
ρb	1.34	.21	.93	1.59	.66

Table 4.--Comparison of water retention values at both energy levels for
the original models and the two new data sets

Retention bars	Data set	n	Average retention	b	Adjusted model	
					$S_{y \cdot x}$	R^2
1/3	Orig.	47	15.1	0.984	2.1	.74
	1	21	16.0	1.001	2.7	.66
	2	15	16.7	.909	2.4	.71
15	Orig.	47	6.2	.982	.9	.73
	1	24	6.7	1.065	1.1	.72
	2	15	6.7	.911	1.2	.70

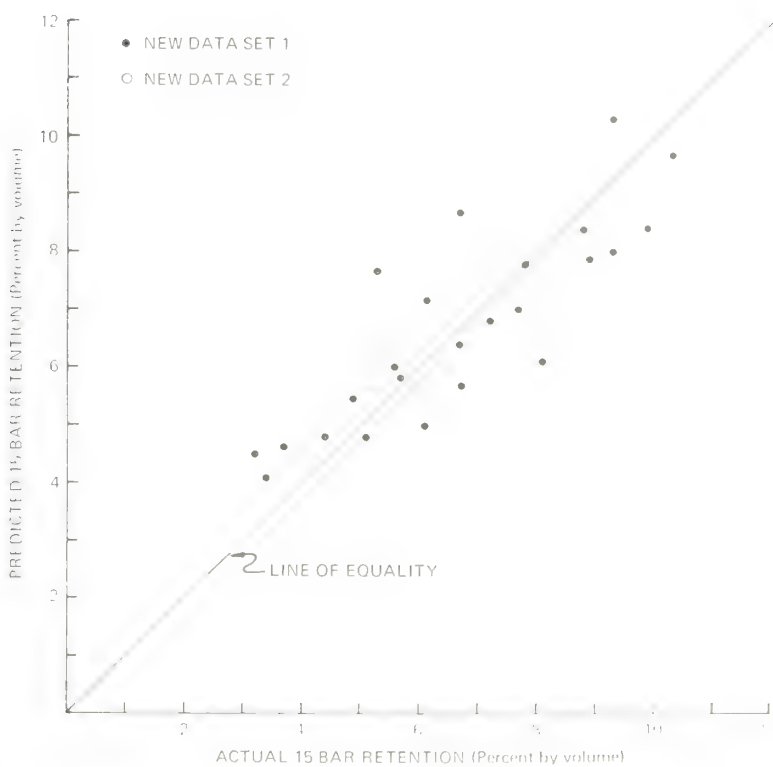
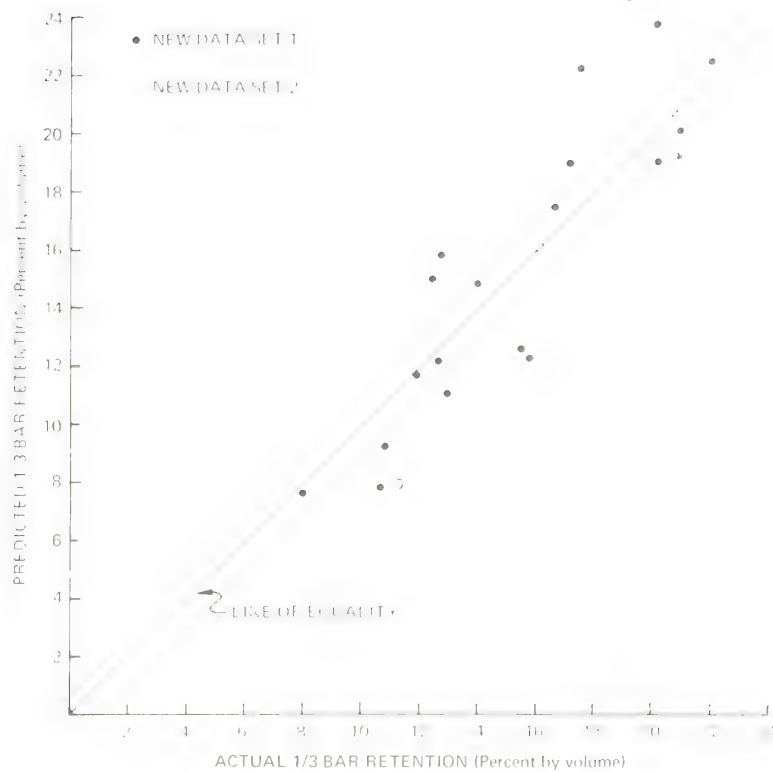


Figure 1.--Plot of predicted 1/3 bar retention versus actual retention for the two new data sets. (The line with 0 intercept is the line of correspondence.)

Visual appraisal of *all* departures shown in figure 8, one-third retention, suggests that the *form* of the original model is especially appropriate in the midrange of actual retention. At the lower extreme, average negative bias in estimated retention maximizes at perhaps 1 percent and average positive bias at 1.5 percent at the upper extreme. So the original model, scaled to the data set from each of two new areas, performed reasonably well when evaluated *jointly* for these applications.

This limited check, at least, shows some promise of the model *form* being applicable for Batholith soils in general. Additional support for this thesis is present in table 4 where the $s_{y,x}$ (standard errors of estimate) are fairly consistent. Note that $s_{y,x} = 2.1$ for the original model is apt to be an underestimate since only two degrees of freedom were charged against the fitting process. Actually an unknown number of degrees of freedom were sacrificed in graphically exhausting the original data set of information.

Applying the same evaluation as above to the 15-bar retention model, an average positive bias of about 1 percent in estimated retention exists at the lower extreme of actual retention, an average of a negative 1 percent at the upper extreme. Although the magnitudes of bias do not seem critical to conventional field applications, the form of the original model seems consistently different for the two new data sets.

CONCLUSIONS

Models developed for predicting water retention at 1/3 and 15 bars tension demonstrate the strong influence of organic matter on water retention in coarse-textured soils of the Idaho Batholith. The models were developed using data from disturbed soil samples, a problem that could not be overcome due to lack of cohesive strength of the soils. At 1/3 bar, the adverse effects of the disturbed soils on retention measurements should be somewhat tempered by the weak structure inherent in the field soils. At 15 bars, almost all water is retained by adsorption, negating the problem of soil sample disturbance.

The original models were developed with the constraint that they fit theoretical expectations over the ranges sampled for the three independent variables: percent by weight organic matter, percent by weight fines (<50 μ m diameter), and bulk density.

Two new data sets with wide geographic variability within the Idaho Batholith were used to test the applicability of the original models. Both sets confirmed the general curve form, and the original model performed reasonably well after least squares adjustment. The second new data set included three soils formed from loess having bulk densities and textures at the limits of the original data used in developing the models. Predicted retention values at both energy values were surprisingly accurate for all three loessal soils.

For several reasons, the authors urge caution in the use of the models for predicting hydrologic and ecologic factors such as water yield and "available soil moisture." Experience in the Batholith has shown that the bedrock is generally highly fractured and often highly weathered to great depths. Deep water storage and utilization of this water by deep rooted plants is universal throughout the Batholith. Drill cores recovered from depths of 800 feet have shown hydrolysis of biotites and iron oxide stains coating mineral grains (unpublished data on file, Intermountain Station, Boise, Idaho). Secondly, the effects of disturbance on the soils disrupted the natural pore size distribution due to soil structure, which almost certainly affected the values determined at 1/3 bar tension. Because of the coarse nature and inherent single grain structure of the Batholith soils, this effect may be minimal, especially at low organic matter and low fines percentages.

The models do have value in estimating soil water regimes necessary in classifying soils at the family level. In addition, they give some estimate of soil water retention in the soil at two energy levels, and have practical value in estimating moisture regimes for revegetation efforts.

Because the regression models were interaction-sensitive, they allowed exhaustion of information from the independent variables within the constraints of theoretical expectation. Modest curve form bias and the close proximity of the standard errors of estimate for the interaction models fitted to the original and to two new data tend to substantiate the general applicability of the original interaction forms. It would, however, probably be advisable to regard the original model forms developed here as applicable on an interim basis, to be improved upon as more data

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APPENDIX

Table 5. Tables for predicting volumetric water retention at 1/3 bar

(A) 10° F								
% OM								
pb	0	2	4	6	8	10	12	
0.9	--	--	8.55	11.6	13.5	14.4	--	
1.0	--	4.57	8.60	11.6	13.5	14.4	--	
1.1	1.66	4.89	8.80	11.8	13.6	14.4	--	
1.2	1.04	5.56	9.56 ^{*1}	12.4	13.9	14.6	--	
1.3	1.36	5.85	9.80	12.5	--	--	--	
1.4	1.64	5.92 [*]	9.92 ^{**}	13.0	--	--	--	
1.5	1.95	7.60 ^{**}	13.1	17.7	--	--	--	
1.6	2.52	8.76	14.9	--	--	--	--	
1.7	2.95	9.40	15.7	--	--	--	--	
1.8	--	--	--	--	--	--	--	

(B) 20° F								
% OM								
pb	0	2	4	6	8	10	12	
0.9	--	--	11.6	15.6	18.1	19.4	19.8	
1.0	--	6.68	11.8	15.7 [*]	18.2	19.4	19.8	
1.1	1.90	7.21	12.2 [*]	16.0 ^{**}	18.4	19.6	20.0	
1.2	2.36	8.28 [*]	13.6 [*]	17.3	19.3	20.2	20.5	
1.3	2.83	9.28 ^{**}	15.0 ^{***}	18.9	21.0	21.9	22.1 [*]	
1.4	3.27	9.85 ^{***}	16.0 [*]	20.7	23.7	--	--	
1.5	3.77	10.3 [*]	16.6 ^{***}	21.8	--	--	--	
1.6	4.61	11.2 [*]	17.7 [*]	23.0 [*]	--	--	--	
1.7	5.25	12.1	18.8 ^{**}	24.3	--	--	--	
1.8	5.69	12.9	19.9	--	--	--	--	

(C) 30° F								
% OM								
pb	0	2	4	6	8	10	12	
0.9	--	--	13.8	18.7	22.2	24.2	25.1	
1.0	--	--	14.1	18.9	22.3	24.3	25.2	
1.1	3.06	8.83	14.5 [*]	19.3 ^{**}	22.6	24.6	25.4	
1.2	3.46	9.96 [*]	16.1 ^{**}	20.8 ^{**}	23.9	25.4 [*]	26.0	
1.3	3.97	10.7 [*]	17.0 ^{**}	21.8	24.8	26.2	--	
1.4	4.47	11.0	17.1	22.1	25.3	27.0	--	
1.5	5.04	11.3	17.4 [*]	22.5	--	--	--	
1.6	5.82	12.2	18.5	23.6	--	--	--	
1.7	6.46	13.1	--	--	--	--	--	
1.8	6.98	13.9	--	--	--	--	--	

(D) 40° F ²								
% OM								
pb	0	2	4	6	8	10	12	
0.9	--	--	14.3 [*]	19.1	22.5	24.5	25.4	
1.0	--	--	14.6 [*]	19.3	22.7	24.6	25.5	
1.1	--	9.33	14.9 [*]	19.6	23.0	24.9	25.7	
1.2	4.06	10.5	16.5	21.2	24.2	25.7	26.3	
1.3	4.57	11.2	17.4	22.1	25.0	26.4	--	
1.4	5.10	11.4	17.5	22.3	25.4	27.1	--	
1.5	5.65	11.8	17.7	22.6	--	--	--	
1.6	6.28	12.6	18.7	23.7	--	--	--	
1.7	6.86	13.4	--	--	--	--	--	
1.8	7.41	14.3	--	--	--	--	--	

¹Asterisks denote data points.²For fines >40% use this table. The authors do not advise use of the model for fines >55%.

Table 6. *Calculated values of the α parameter for different values of β and γ*

$\lambda = 10^\circ$							
OM							
$\rho\beta$	0	2	4	6	8	10	12
0.9	-	-	4.08	5.69	6.90	-	-
1.0	-	2.51	4.22	5.77	7.03	-	-
1.1	1.82	2.72	4.44	5.95	7.24	8.30	-
1.2	1.07	3.00	4.74* ¹	6.11	7.58	-	-
1.3	1.86	3.35	5.14	6.72	-	-	-
1.4	1.69	3.59*	5.66**	7.81	-	-	-
1.5	2.04	4.30**	6.31	8.07	-	-	-
1.6	2.39	4.86	7.03	-	-	-	-
1.7	2.70	5.30	7.57	-	-	-	-
1.8	-	-	-	-	-	-	-
$\lambda = 20^\circ$							
OM							
$\rho\beta$	0	2	4	6	8	10	12
0.9	-	-	4.66	6.26	7.66	-	-
1.0	-	3.05	4.81	6.49*	7.70	-	-
1.1	1.34	3.26	5.02*	6.61**	8.01	9.14	10.1
1.2	1.60	3.54*	5.32*	6.97*	8.31	9.74	10.5
1.3	1.89	3.89**	5.72***	7.37*	8.82	10.1	11.3*
1.4	2.22	4.32***	6.23*	7.96	-	-	-
1.5	2.57	4.83*	6.88***	8.71	-	-	-
1.6	2.92	5.39*	7.60*	9.54*	-	-	-
1.7	3.23	5.84	8.15**	10.1	-	-	-
1.8	3.41	6.04	8.37	-	-	-	-
$\lambda = 30^\circ$							
OM							
$\rho\beta$	0	2	4	6	8	10	12
0.9	-	-	5.27	6.93	8.40	9.67	10.7
1.0	-	-	5.42	7.07	-	9.79	10.7
1.1	1.87	3.83	5.64*	7.28**	8.77	10.0	11.0
1.2	2.13	4.11*	5.93**	7.60**	9.18	10.4*	11.4
1.3	2.42	4.45*	6.33***	8.04	9.76	-	-
1.4	2.75	4.88	6.84	8.62	10.2	11.6	-
1.5	3.10	5.39	7.49*	9.38	-	-	-
1.6	3.45	5.95	8.22	10.1	-	-	-
1.7	3.76	6.40	-	-	-	-	-
1.8	3.94	6.61	-	-	-	-	-
$\lambda = 40^\circ$							
OM							
$\rho\beta$	0	2	4	6	8	10	12
0.9	-	-	5.46*	7.17	8.60	9.89	10.9
1.0	-	-	5.61*	7.26	8.74	10.0	11.1
1.1	-	4.02	5.83*	7.47	8.95	10.2	11.3
1.2	2.33	4.30	6.12	7.79	9.28	10.6	11.6
1.3	2.63	4.65	6.52	8.23	9.76	11.1	-
1.4	2.96	5.07	7.02	8.81	10.4	11.8	-
1.5	3.31	5.59	7.68	9.57	-	-	-
1.6	3.65	6.15	8.40	10.41	-	-	-
1.7	3.96	6.59	-	-	-	-	-
1.8	4.15	6.80	-	-	-	-	-

¹Asterisks denote data points.²For fines >40 μ use this table. The authors do not advocate of the model for fines >55 μ .

$$Y = 1/3 \text{ bar retention} = f (\%OM, \%F, \rho b)$$

$$(1) \quad Y = \left\{ \text{LEDG} + (\text{REDG} - \text{LEDG}) \left\{ \frac{e^{-\left| \frac{\frac{OM}{15} - 1}{1 - I} \right|^N} - e^{-\left| \frac{1}{1 - I} \right|^N}}{1 - e^{-\left| \frac{1}{1 - I} \right|^N}} \right\} \right\} 0.984$$

$$(2) \quad \text{REDG} = 15 + (\text{RR} - 15) \left\{ \frac{e^{-\left| \frac{\frac{F}{55} - 1}{1 - RI} \right|^{10}} - e^{-\left| \frac{1}{1 - RI} \right|^{10}}}{1 - e^{-\left| \frac{1}{1 - RI} \right|^{10}}} \right\}$$

$$\text{RR} = 26 + 9.9812 (\rho b - 0.9)^{2.1}$$

$$\text{RI} = 0.05 + 0.295 e^{-\left| \frac{\left(\frac{1.8 - \rho b}{0.9} - 1 \right)}{0.63} \right|^{6.8}}$$

$$(3) \quad \text{LEDG} = \text{LR} \left\{ \frac{e^{-\left| \frac{\frac{F}{55} - 1}{1 - LI} \right|^{LN}} - e^{-\left| \frac{1}{1 - LI} \right|^{LN}}}{1 - e^{-\left| \frac{1}{1 - LI} \right|^{LN}}} \right\}$$

$$\text{LR} = 2.9 + 5.278 (\rho b - 0.9)^{1.1}$$

$$\text{LI} = 0.4017 e^{-\left| \frac{\frac{\rho b}{0.9} - 1}{0.39} \right|^{1.8}} - 0.0017$$

$$\text{LN} = 4 - e^{-\left| \frac{\frac{\rho b}{1.34} - 1}{0.1865} \right|^{4.6}}$$

$$(4) \quad N = NREDG + NYP \left\{ \frac{e^{-\left| \frac{\left(\frac{55 - F}{55} - 1 \right)}{1 - NSI} \right|^{20}} - e^{-\left| \frac{1}{1 - NSI} \right|^{20}}}{1 - e^{-\left| \frac{1}{1 - NSI} \right|^{20}}} \right\} \quad \text{N. III}$$

$$NREDG = 3.5 + 0.45 \, e^{-\left| \frac{\left(\frac{\rho_b}{1.28} - 1 \right)}{0.1} \right|^4}$$

$$NSI = 0.53 + 0.07 \, e^{-\left| \frac{\left(\frac{1.8 - \rho_b}{0.9} - 1 \right)}{0.35} \right|^{10}}$$

$$NYP = 0.5 + 0.05 \, e^{-\left| \frac{\left(\frac{\rho_b - 0.9}{0.9} - 1 \right)}{0.7} \right|^{20}} - 0.55 \, e^{-\left| \frac{\left(\frac{\rho_b - 1.9}{0.785} - 1 \right)}{0.4} \right|^{20}}$$

$$NSUB = 0.1 \left\{ e^{-\left| \frac{\left(\frac{1.8 - \rho_b}{0.9} - 1 \right)}{0.35} \right|^{10}} \right\} \left\{ e^{-\left| \frac{\left(\frac{1}{52.5} - 1 \right)}{0.58} \right|^{10}} \right\}$$

$$(5) \quad I = 0.01$$

OTE: $0 < OM \leq 15$
 $0.9 \leq \rho_b \leq 1.8$
 $0 \leq F \leq 55\%$

Y = 15 bar retention = f (%OM, %F, ρb)

$$(1) \quad Y = \left\{ \text{REDG} - \left\{ \frac{(\text{REDG} - \text{LEDG})}{15^N} \right\} (15 - \text{OM})^N \right\} 0.982$$

$$(2) \quad \text{REDG} = \text{RL} + 2.9 e^{-\left| \frac{\frac{F}{55} - 1}{0.7} \right|^5}$$

$$\text{RL} = 9.2 + 4.686 e^{-\left| \frac{\frac{(\rho b - 0.9)}{0.7} - 1}{0.5} \right|^2} - 0.086$$

$$(3) \quad \text{LEDG} = \text{LL} + 1.478 e^{-\left| \frac{\frac{F}{55} - 1}{0.682} \right|^{4.3}} - 0.008$$

$$\text{LL} = 0.28 + 3.054 e^{-\left| \frac{\frac{(\rho b - 0.9)}{0.9} - 1}{0.7} \right|^{1.5}} - 0.554$$

$$(4) \quad N = \text{NFLOR} + \text{NSIG} e^{-\left| \frac{\frac{(\rho b - 0.9)}{0.9} - 1}{0.31} \right|^3}$$

$$\text{NFLOR} = 1.488 + 0.212 e^{-\left| \frac{\frac{(\rho b - 0.9)}{0.9} - 1}{0.31} \right|^3}$$

$$\text{NSIG} = 3.704 \times 10^{-6} (55 - F)^{2.8} + 0.05 e^{-\left| \frac{\frac{(55 - F)}{47} - 1}{0.16} \right|^2}$$

NOTE: $0 \leq \text{OM} \leq 15\%$
 $0.9 \leq \rho b \leq 1.8$
 $0 \leq F \leq 55\%$

CLAYTON, JAMES L., and CHESTER E. JENSEN

1973. Water retention of granitic soils in the Idaho Batholith. USDA Forest Serv. Res. Pap. INT-113, 20 p., illus. Intermountain Forest & Range Experiment Station, Ogden, Utah 84401.

Volumetric water retention at 1:3 and 1:5 bars was evaluated for strength of retention to the interacting effects of percent organic matter, percent fines < 50 μ m diameter, and soil bulk density for soils from the Idaho Batholith. Organic matter was the strongest of the variables affecting retention in these coarse soils. The final models were adjusted by least squares to two new data sets of geographically diverse soils from the Idaho Batholith. The adjusted retention models operate surprisingly well for predicting water retention at both energy levels.

OXFORD: 114.124:114.1: KEYWORDS: water retention, granitic soils.

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CLAYTON, JAMES L., and CHESTER E. JENSEN

1973. Water retention of granitic soils in the Idaho Batholith. USDA Forest Serv. Res. Pap. INT-113, 20 p., illus. Intermountain Forest & Range Experiment Station, Ogden, Utah 84401.

Volumetric water retention at 1:3 and 1:5 bars was evaluated for strength of retention to the interacting effects of percent organic matter, percent fines < 50 μ m diameter, and soil bulk density for soils from the Idaho Batholith. Organic matter was the strongest of the variables affecting retention in these coarse soils. The final models were adjusted by least squares to two new data sets of geographically diverse soils from the Idaho Batholith. The adjusted retention models operate surprisingly well for predicting water retention at both energy levels.

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POSSIBILITIES FOR IMPROVEMENT OF WESTERN WHITE PINE BY INBREEDING

Richard T. Bingham



INTERMOUNTAIN FOREST AND RANGE
EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHOR

RICHARD T. BINGHAM is a research scientist with the Moscow, Idaho, Forestry Sciences Laboratory research unit studying genetics and pest resistance in northern Rocky Mountain conifers. He has had broad experience in the pathology, silviculture, and genetics of western white pine; also, he is author of numerous publications on the genetics of blister rust resistance, and on the genetics of western white pine.

Cover Photo.--Growth differences are evident between this 20-year-old S_1 tree (63 X 63) No. 3 (left) and one of its 20-year-old half-sibs (63 X 62) No. 2 (right), at the Moscow Arboretum, December 1972.

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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Robert W. Harris, Director

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ABSTRACT

Pinus monticola S_1 seedling mortality, timing and extent of fruiting, strobilus attrition, crossing success, seed yield, and seed weight are compared for 18 S_1 lines and their outcrossed half-sib lines. No reproductive barriers are restrictive enough to preclude continued inbreeding. Filled seed yields from second generation inbreeding are low but consistent and large enough to justify continuing an experimental program. Results of experimental single crossing between S_1 lines should guide decision on a practical inbreeding program.

INTRODUCTION

Investigations of the effects of inbreeding in western white pine (*Pinus monticola* Dougl.) have been underway at this Station since 1950 (Bingham and Squillace 1955). Over 150 S_1 seedling lines have been developed, each usually produced along with four full-sib outcrossed seedling lines of the same mother tree (i.e., half-sibs of the S_1 's). S_1 's and their outcrossed half-sib seedlings (hereafter called half-sibs) have been artificially inoculated with the white pine blister rust fungus (*Cronartium ribicola* J. C. Fisch. ex Rabenh.), and seedlings that survived the rust exposure (ranging from 0 to 20 S_1 's and 5 to 30 half-sibs) have been established in a blister rust resistance arboretum at Moscow, Idaho.¹ The oldest of these resistant seedlings are now 21 years of age. There has been substantial fruiting of the half-sib seedlings for about 10 years, but only sporadic fruiting of the S_1 seedlings for about 5 years, with the first substantial fruiting in 1972.

Blister-rust-inoculated S_1 seedling lines have been of immediate value for supporting hypotheses on the presence of recessive resistance genes in western white pine (McDonald and Hoff 1971). Now that the S_1 lines are reaching reproductive maturity, however, they are becoming useful for assessing possibilities and limitations of classical inbreeding methods (Shull 1910; Jones and Singleton 1935) for improvement of growth and other traits.

This paper considers the feasibility of an inbreeding program in western white pine, its likely timing and promise. Data presented here are mainly restricted to cone and seed bearing following controlled crossings on 18- to 21-year-old S_1 trees in 18 different lines. Second-generation inbred cone yields and seed progenies discussed include those from selfing S_1 trees (S_2 crosses), S_1 full-sib crosses, S_1 backcrosses, single crosses (between unrelated S_1 's), and other inbred crosses of the second and first generation. Descriptions and examples of these inbreds are given in "Materials and Methods," starting on page 5.

¹Progress reports on breeding for blister rust resistance in western white pine include Bingham and others 1953, 1960, 1969, and 1972.

LITERATURE REVIEW

An extensive literature deals with effects of first-generation selfing in conifers, especially *Pinus*. The summary by Franklin (1970) covers much of this literature through 1967, and adequately describes effects of inbreeding as reflected in S_1 cone and seed yields, seed germination, and mortality and early growth of S_1 seedlings. His table 3 sums up these S_1 effects in *Pinus*, pointing out that in general, and in comparison to outcrossing, neither cone yield nor total (filled plus hollow) seed yield are affected, filled seed yield is reduced about one-third, hollow seed yield is increased about 2-1/2 times, seed germination is reduced about one-tenth, seed weight is little affected, seedling mortality is about one-third higher, and seedling height is reduced about one-fourth.

These general conclusions are quite applicable to western white pine, except that in young trees (18 to 21 years) cone yield may be reduced, if not in the older trees (30 to 50 years) covered by Franklin.

Several times in the past (Bingham and Squillace 1955; Squillace and Bingham 1958; Barnes and others 1962) we have noted the wide variation in self-fertility of different western white pine mother trees. Some trees are comparatively self-fertile, others self-sterile, in respect to seed yield, as is shown in table 1. The self-fertile trees like parent 58 are equal or better in filled S_1 seed yield and give somewhat greater hollow seed yield. The seat, manner of operation, and timing of the incompatibility mechanisms are unknown, but the effect is strongly associated with the mother tree.

In contrast, literature on second-generation inbred crossing is very sparse. Only five reports of crossing of S_1 trees have been found. Some of this information was outlined by Franklin (1970), but is reviewed more completely in this paper, so that sounder conclusions may be drawn as to the feasibility of continued inbreeding or the likelihood of improvement of conifers by use of classical inbreeding methods.

Table 1.--Seed yield, seed weight, and seedling emergence, for a comparatively self-fertile and a comparatively self-sterile western white pine tree¹

Pollination year	Type of cross	Number of crosses	Filled seed per cone ²	Hollow seed per cone ²	Seed weight ²	Seedling emergence ²
SELF-FERTILE TREE 58						
1950	Self	1	134			84
	Outcross	11	106			87
1954	Self	1	88	44	18.1	52
	Outcross	2	68	36	17.4	42
1957	Self	1	103	20	18.2	
	Outcross	1	121	4	19.1	
All years	Selfs	3	108			
	Average outcrosses	14	98			
SELF-STERILE TREE 19						
1950	Self	1	24			83
	Outcross	18	35			84
1954	Self	1	31	63	22.4	58
	Outcross	1	61	14	22.1	64
All years	Selfs	2	28			
	Average outcrosses	19	40			

¹Data from Bingham and Squillace (1955), Squillace and Bingham (1958), and Barnes and others (1962).

²Results for groups of outcrosses are average values.

³Emergence of seedlings in the nursery seedbeds is probably less than their total germination.

The oldest material reported upon in the literature concerns five 55-year-old Norway spruce (*Picea abies* (L.) Karst.) S_1 trees in two S_1 lines developed by Swedish silviculturist Nils Sylven through self-pollinations made in 1909! Langlet (1940), and later Eriksson and others (1973) reported upon inbreeding effects in this very old material. Andersson (1965) selfed the five S_1 trees. Four of the S_1 's produced cones, three produced filled S_2 seeds. Cone and S_2 seed yields are given in "Discussion," starting on page 12, where they are compared with those of three other conifers, including western white pine. About one-half, or 21, of the filled S_2 seed in three different S_2 seed lots germinated in a Jacobsen germinator, but no information is given on their subsequent survival and growth. Andersson noted that a greater reduction in germination occurred between outcrosses and S_1 seed than between the S_1 and S_2 seed.

Dr. Wolfgang Langner produced S_1 's of Japanese larch (*Larix leptolepis* (Sieb. & Zucc.) Gord.) in Germany from self-pollinations made in 1936. Later, Langner (1961) reported upon second-year height of S_2 's coming from these S_1 's, and on related progenies, as shown below.

	<i>Outcrosses</i>	<i>Half-sibs</i>	<i>Full-sibs</i>	<i>S₂'s</i>
Inbreeding coefficient (F)	0.000	0.125	0.250	² 0.750
Average height (cm)	37.3	32.7	29.7	24.7

Just a few years later in 1938 and 1941, Dr. C. Syrach Larsen also selfed Japanese larch, as well as European larch (*Larix decidua* Mill.). Later, Keiding (1962) crossed the Japanese and European larch S_1 's, noting that the single cross interspecies hybrids produced outgrew the parents. Effects of inbreeding within species could not be separated, however, from effects of interspecies hybridization: Keiding stated, "It was not possible to prove any additional effects of inbreeding and outcrossing."

The next oldest material is that of Orr-Ewing (1954, 1965, 1969). Self-pollinations of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) parental trees were begun in 1952, and continued through 1968. Within 8 to 10 years about one-third of the S_1 trees in seven out of eight S_1 families (1 to 98 trees per line) were producing an average of 10 to 14 female strobili per tree (Orr-Ewing 1965). In the same time, S_1 's in only three of the eight families produced male strobili. Amounts of pollen ranged from inadequate for a single pollination to enough for four or more pollinations. Outcrossed sibs of the same parent trees had almost twice as many sporophylls per male strobilus, but pollens of S_1 's or outcrossed sibs were indistinguishable. Orr-Ewing (1965) went on to show that on the average about half of the filled S_2 seed germinated (here in eight S_2 lines), and finally, that the average first-year height of S_2 seedlings in six lines varied between 27 and 59 mm. Many S_1 backcrosses, S_1 sib crosses, and two single crosses were also reported upon. Cone and seed yields of the S_2 and these crosses also are given in "Discussion," starting on page 12. Orr-Ewing (1969) reinforced his earlier finding of variability in average height of 1-year-old S_2 seedling families (range 79 to 158 mm). His general conclusions (Orr-Ewing 1954, 1965, 1969) were that in Douglas-fir, inbreeding would be sufficiently rapid and easy to be entirely feasible, and that variation in inbreds was great enough so that an inbreeding program probably would be rewarding. Some of the single-cross progenies looked quite promising, and selection among S_1 's would have had pronounced effects on single cross seedlings. Unfortunately, no control (outcrossed) seedlings were compared with the single cross seedlings.

The youngest material reported upon is that of Katsuta (1966), who began selfing Japanese black pine (*Pinus thunbergiana* Franco) and the Japanese red pine (*Pinus densiflora* Sieb. and Zucc.) in 1956. Within 7 to 8 years, S_1 trees of Japanese black pine were fruiting so that S_2 's and S_1 sib crosses, S_1 backcrosses, and single crosses could be attempted. Cone and seed yield from these second-generation inbred crossings also are given in "Discussion," starting on page 12. Apparently second-generation inbred seeds were not sown. Katsuta remarked that S_2 seed yields were "considerably high."

Useful comparisons have been made of the association of certain characteristics with increasing inbreeding coefficient F. Langner (1961) showed a decrease of about 5 percent in height of 2-year-old Japanese larches, and Squillace and Kraus (1962) showed decreases of five seed per cone and 8 percent in germination in 1-year-old slash pine (*Pinus elliottii* var. *elliottii* Engelm.), for each 0.1 increase in F.

²Given by Langner as 0.625.

MATERIALS AND METHODS

Between 1950 and 1970, first-generation selfings were attempted on about 200 western white pines in natural stands of northern Idaho. Seed and S_1 seedling lines were produced from more than 150 of these selfs, but seedlings of only about 50 S_1 lines remained after blister rust resistance testing. The resistant S_1 seedlings were transplanted into the blister rust resistance arboretum, where in 1972 they ranged from 8 to 21 years of age. The trees below age 18 so far have fruited very infrequently, however. Therefore, only 109 S_1 trees in the 18- to 21-year-old age bracket, one to 18 trees in each of 22 S_1 lines, constitute the inbred materials covered in this paper. At present only 72 of these S_1 's in 18 different lines survive. Some S_1 's in 17 of the 18 surviving S_1 lines have fruited. Outcrossed materials for comparison consist of over 1,000 surviving trees in 158 lines. All outcrossed trees are half-sibs of the S_1 trees, and of the same ages. These half-sib trees occur in 140 full-sib and 18 wind-pollinated progenies of the same 22 mother trees, and there are from 4 to 235 trees in each of the 22 mother-tree lines.

Female strobilus production on S_1 's began in 1960, when single 9-year-old S_1 trees of two lines produced one or two strobili. Although pollinated, none of the three strobili developed beyond that juvenile stage. The first mature cones and filled S_1 trees were produced on 11-year-old S_1 's in 1962, from 1961 pollinations. Male strobilus production on S_1 's was delayed until 1966, and then occurred only on a single 13-year-old tree. By 1972, however, some S_1 lines were producing large volumes of pollen (up to 35,000 male strobili), and one S_1 line had produced male strobili every spring for 6 years. Complete records on both female and male strobilus production were maintained on all trees in the arboretum through 1966. Thereafter, because female fruiting became so general and abundant, only male strobilus counts were continued.

Over the 13 years since female strobilus production commenced on S_1 trees, many kinds of inbred matings have been attempted on the S_1 's or on their half-sibs. Before S_1 pollens became available, the S_1 's that bore female strobili were backcrossed to their natural-stand parents or outcrossed to other natural-stand parents, using stored pollens. Then, as the related but outcrossed half-sibs began producing pollen, the S_1 's were mated with these in half-sib crosses, or the related half-sibs were themselves crossed in half- and full-sib, backcross, self, or outcross matings. Finally, and mainly in the last 5 years after S_1 male strobilus production attained substantial proportions, S_2 crosses, S_1 full-sib crosses, S_1 backcrosses, and single crosses between S_1 's of two different lines were attempted. Thus, cone and seed yields from inbreds representing a range of levels of inbreeding ($F = 0.125$ to 0.750) can be compared. These inbred yields can also be compared with those from the outcross population of 158 related half-sibs.

The various first- and second-generation inbred crosses compared may be clearly understood from examples of their pedigrees (table 2). In calculating the inbreeding coefficients, original parents were assumed not to be inbred.

Table 2.--Types of crosses and examples of pedigrees of western white pine trees supplying study data

Type of cross	: Number of : crosses : attempted	Arboretum female parent		:	Arboretum male parent		:	Inbreeding : coefficient : (F)
		F ₁ or S ₁ line	Sibling : number		F ₁ or S ₁ line	Sibling : number		
		Female : Male			Female : Male			
Population outcross	642	(19 x 1)		X	(58 x 17)			¹ 0.000 ⁺
Half-sib cross	35	(19 x 1)		X	(58 x 19)			0.125
Full-sib cross	87	(19 x 1 - 1)		X	(19 x 1 - 2)			0.250
First generation backcross	134	(19 x 1)		X	19 (original parent)			0.250
S ₁ X outcross	4	(19 x 19)		X	(58 x 17) or x 58 (original parent)			0.000
S ₁ single cross (crossing of unrelated S ₁ 's)	67	(19 x 19)		X	(58 x 58)			0.000
S ₁ X half-sib	3	(19 x 19)		X	(19 x 58)			0.250
S ₁ cross (selfing of an F ₁)	46	(19 x 58 - 1)		X	(19 x 58 - 1)			0.500
S ₁ backcross	60	(19 x 19)		X	19 (original parent)			0.500
S ₁ X full-sib	22	(19 x 19 - 1)		X	(19 x 19 - 2)			0.500
S ₁ X self (S ₂ cross)	9	(19 x 19 - 1)		X	(19 x 19 - 1)			0.750

¹Degree of inbreeding in natural populations is unknown, but the coefficient probably exceeds zero.

RESULTS

Various trees, both S_1 's and outcrossed half-sibs, many represented by only a few trees per line, could be crossed only to the extent of their variable and often limited female or male fruiting. An extremely uneven mating pattern resulted, rendering many statistical analyses impractical. The only analyses attempted are estimations of the significance of the mean differences between S_1 's and their related but outcrossed half-sib lines as to mortality, timing and extent of strobilus production, success of crossing, female strobilus loss, numbers of filled and hollow seeds, and seed weight (table 3). The body of data is large enough, however, to allow conclusions on the limitations and practicality of continued inbreeding in western white pine to be drawn with some confidence.

Survival of S_1 Trees

In 22 S_1 lines, a total of 109 trees survived exposure to the blister rust fungus in the nursery and were transplanted into the arboretum. Of these, 72, or 66 percent, survived in 1972, or at least had fruited prior to death (table 3). In comparison, 92 percent of the 1,014 outcrossed trees, in 140 full-sib and 18 wind-pollinated lines, all half-sib to one or the other of the S_1 lines, survived or had fruited. More than 25 percent lower survival in S_1 's was significant. Nevertheless, survival was adequate for proceeding with second-generation inbreeding. Survival seems to be somewhat higher in S_1 lines from self-fertile parents like 25 and 58.

Comparative Delay and Extent of Fruiting of S_1 Trees

Onset of fruiting, and its extent in seasons fruited, proportion of trees fruiting, and total number of strobili borne are also shown in table 3, for 18 surviving S_1 lines and their corresponding outcrossed half-sib lines. It is remarkable that bearing of female strobili by S_1 's as compared with outcrosses is delayed only about 3 years, and that a higher proportion (more than 20 percent) of the S_1 trees bore female strobili. Perhaps female fruiting is under control of one or a few recessive genes, and thus is enhanced by selfing. Otherwise, all features of timing and extent of female fruiting are in favor of the outcrossed half-sibs. In the S_1 trees, male fruiting is delayed more than two, probably several, years. Female strobili are borne only two-thirds as frequently, male strobili one-fifth as frequently; over 20 percent fewer trees produce male strobili; and total strobilus counts are only one-fourth (female) to one-sixth (male) as great as in the related half-sibs.

Table 3.-Comparison of western white pine S_1 trees and outcrossed trees (half-sibs of the S_1 's) as to tree survival, timing and extent of fruiting, attrition of female strobili, and seed production and weight

Parent (mother) tree number	Type of tree crossed	Different half-sib lines	Trees planted/ trees sur- viving ²	Age of trees in 1972 (5)	Avg. age : 1st female: years female: : strobili: borne	Different strobili: borne	Avg. age: Different : 1st male: years male: : strobili: borne	Different strobili: borne	Total strobili: borne per avg. tree all years	Female	Male	Female	Male
1)	2)	(3)	(4)		(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
				Years	Years		Years						
1	S ₁ half-sib	4	2/1 14/12	19 18, 20, 21	15.0 10.3	3 4	519* 10.2	0 5	1 4	0 6	0 2	0 325	0
16	S ₁ half-sib	8	2/1 38/34	18 18-21	16.0 10.2	1 7	18* 16.6	0 6	1 20	0 13	0 7	0 550	0
17	S ₁ half-sib	6	8/2 74/70	18 18-21	14.5 10.9	6 10	16.6 17.6	3 9	2 42	1 37	0 7	585 2295	0
18	S ₁ half-sib	5	1/0 22/21	18-21									
19	S ₁ half-sib	33	17/12 251/235	21 18-21	14.0 11.0	8 13	17.5 17.5	3 9	11 152	2 102	2 8	1 1100	1
20	S ₁ half-sib	12	1/1 69/65	19 19-21	19.0 11.0	0 9	19* 18.3	0 9	0 39	0 26	0 6	0 870	0
21	S ₁ half-sib	4	4/3 45/43	19 18-21	13.5 11.3	5 10	19.0 17.3	1 9	2 40	1 31	1 15	250 4830	0
22	S ₁ half-sib	8	4/3 103/105	21 18, 19, 21	15.5 11.6	5 12	21* 17.1	0 11	2 78	0 70	1 12	0 2400	0
24	S ₁ half-sib	1	2/2 4/4	18 18&21	11.5 12.0	4 4	18* 14.3	0 5	2 2	0 3	1 26	0 2640	0
25	S ₁ half-sib	8	7/6 42/41	19 18-21	10.5 11.3	9 8	19.0 15.9	1 8	6 33	1 21	9 14	30 1045	0
30	S ₁ half-sib	4	2/2 19/17	19&21 18&21	12.0 9.8	2 5	20* 16.4	0 3	1 13	0 5	1 11	0 230	0
37	S ₁ half-sib	75	3/0 23/23	18&21									
39	S ₁ half-sib	5	1/1 15/14	21 18&21	10.0 10.6	7 3	18.0 18.7	1 3	1 7	1 5	13 4	105 390	0
45	S ₁ half-sib	2	2/0 7/7	18&21									
54	S ₁ half-sib	12	6/2 54/48	20 18-20	12.0 11.2	1 5	20* 16.9	0 5	1 18	0 8	1 1	0 185	0
58	S ₁ half-sib	19	18/18 182/163	21 18, 20, 21	13.1 11.4	12 13	18.7 17.0	6 9	15 114	10 86	7 10	745 3115	0
59	S ₁ half-sib	7	3/1 17/14	19 19&20	14.0 11.2	2 2	16.0 17.8	4 5	1 8	0 8	0 6	2200 3480	0
61	S ₁ half-sib	72	3/1 7/6	18 18	13.0 9.0	3 2	13.0 9.0	1 2	1 1	1 1	0 0	3 0	0
63	S ₁ half-sib	6	7/6 54/48	20 18-20	15.6 11.3	6 8	20.0 17.9	1 8	5 27	1 22	0 4	3 1305	0
65	S ₁ half-sib	3	5/3 19/17	19 18-19	12.0 10.5	3 2	18* 15.5	0 2	4 3	0 4	0 0	0 665	0
69	S ₁ half-sib	4	10/6 10/10	19 19	14.0 10.5	8 4	13.0 19.0	2 1	5 3	1 1	0 4	1 2	0
70	S ₁ half-sib	4	1/0 17/17	18&19									
Totals	S ₁ half-sib	158	109/72 1096/1014	348 347	246.2 195.1	85 121	338.2* 305.8	21 106	61/72 604/946	18/72 446/946	36 137	5920 25427	0
Means	S ₁ half-sib		66.0 92.5	19.3 19.3	13.7 10.8	4.7 6.7	19.9 18.0	1.2 6.2	84.7% 63.8%	25.0% 47.1%	2.2 8.6	230.6 1495.7	0
diff. from			-26.5**	0.0	+2.9**	-2.0*	+1.9*	-5.0**	+20.9**	-22.1*	-6.4**	-1265.1	0

are trees of the first selfed generation from the specified mother trees; half-sibs are either control-pollinated, full-sibs or wind-pollinated "half-sib" trees of the same mother tree, from a given number of different sib lines; all are half-sibs of the mother trees.

* Planted trees excluded those dying from blister rust before fruiting; surviving trees include those alive in 1972, plus those that died prior to death.

Except on trees being bred for special purposes (S₁'s, a few full-sibs, etc.), arboretum-wide observations on female fruiting date continued once it became general (after 1966). Observations on male fruiting, however, are complete through 1972. Thus total female strobili per average tree are compared only through 1966, total male strobili through 1972.

*The five developmental stages correspond to (1) buds small to large (scales not open, prior to or at time of pollination bagging), (2) maximum receptivity (pollination time), (3) strobilus scales closed (time of pollination bag removal), (4) strobili persistent to the end year (time of cone insect bagging), and (5) mature cones (time of cone collection).

The + symbol indicates that the S₁ or sib lines had not produced strobili through 1972. For purposes of comparing pairs of values, the lines were treated as though they all produced strobili in 1973 (i.e., 18+ = 19, 19+ = 20, etc.).

*Dashes in blank cell indicate that phenomenon occurred but was not observed.

Crossing Success as Measured by Production of Mature Female Cones and Filled Seeds on S_1 's

On S_1 's, as compared with outcrosses, about 20 percent fewer of the second-generation inbred crosses attempted resulted in production of mature cones, 30 percent fewer resulted in production of filled seeds, and less than one-fourth as many filled seeds per cone were produced (table 3). Losses of female strobili on S_1 trees, between the unopened bud stage and mature cone stage, are twice as great (78 vs. 39 percent) as on the related, outcrossed trees (table 3). Almost two-thirds of this attrition in female strobili (58 of 78 percent) occurs the first year--either before or shortly after the scales open and the strobili are pollinated (31 percent), or before "setting" of the strobilus at the time of scale swelling and strobilus closure (27 percent). Apparently, these losses are not due to pollination failures, but reflect the reduced ability of the S_1 mother trees to support and mature normal strobili. Again, the effect seems to be least pronounced in the S_1 's from comparatively self-fertile mother trees (25 and 58, vs. 19).

Once mature cones are borne, filled seed yield may be nil (6 crosses of S_1 's of mother tree 19), low but consistent (41 crosses of S_1 's of tree 58), or even consistently good (18 crosses of S_1 's of tree 25). The average yield from mature cones produced in 79 crosses made on S_1 trees of 15 different lines was 10.0 filled seed per cone.

In table 3, the crosses of S_1 's parents are considered only as a group--they are not classified as S_2 's, S_1 X full-sib, etc. In table 4, however, crossing success, attrition of female strobili, and mature cone and seed yields are considered according to type of cross. Besides data for the second-generation inbred crosses, table 4 also provides data for a base outcross population as well as for various types of first-generation inbred crosses (half-sib, full-sib, backcross, and S_1 matings). Types of matings are arranged in order of increasing inbreeding coefficient.

All types of first- and second-generation inbred matings produced some mature cones and filled seeds (table 4). In general, where there is a base of more than a few attempted crosses, at higher levels of inbreeding fewer of the crosses produced mature cones, and filled seed yields were lower. The majority of cones from second-generation inbred matings that reach maturity contain filled seeds, however. There is little failure late in the reproductive process.

Table 4.--Cone and seed yields in relation to level of inbreeding in crosses of western white pine trees

Type of cross	Inbreeding coefficient (F)	Live female strobili at successive developmental stages					Loss, crosses					Seeds per cone, average				
		Crosses attempted	Crosses	Bud	Pollen receptive	Scales closed	Overwintered	Mature cone	buds to mature	Loss, crosses	yielding	filled	seed	Filled	Hollow	
Population outcross	10.000 ⁺	642	5173	4721	--	--	--	3156	35.8	510	79.4	489	76.2	46.8	33.0	
S ₁ outcross	0.000	4	7	7	--	--	--	4	42.8	1	14.3	1	14.3	264.7	16.8	
S ₁ single cross	0.000	67	519	413	203	116	98	98	81.1	32	47.8	30	44.8	16.9	23.9	
Half-sib cross	0.125	35	337	264	208	182	169	169	49.9	29	82.8	28	80.0	40.0	26.6	
Full-sib cross	0.250	87	836	712	596	496	448	448	46.4	65	74.7	61	69.0	30.8	34.3	
Backcross	0.250	154	690	612	588	467	443	443	35.8	108	80.6	107	79.1	39.9	43.4	
S ₁ x half-sib	0.250	3	30	30	17	11	10	10	66.7	2	66.7	2	66.7	15.6	18.6	
S ₁ cross	0.500	46	459	4437	341	275	266	266	42.0	38	82.6	37	80.4	30.1	54.9	
S ₁ backcross	0.500	60	345	302	231	135	105	105	69.6	36	60.0	28	45.0	12.3	40.4	
S ₁ x full-sib	0.500	22	250	158	116	71	64	64	74.4	16	72.7	11	50.0	6.2	26.7	
S ₁ cross	0.750	9	111	92	67	36	35	35	68.5	7	77.8	6	66.7	2.5	20.1	

Degree of inbreeding in natural populations is unknown, but the coefficient probably exceeds zero. Yield from four cones of one cross with an exceptionally self-fertile parent (No. 25).

DISCUSSION AND CONCLUSIONS

The feasibility and efficiency of an inbreeding program depend upon five conditions:

Survival of inbred plants to fruiting age

Fruiting within a reasonable time, and by a reasonable proportion of the plants

Success of the inbred pollinations, or attainment of useful levels of filled seed production

Germination, survival, and fruiting of successive generations of inbred seed and seedlings

Restoration of reproductive vigor (seed bearing) when inbreds are finally outcrossed

The record on the first four of these conditions is reasonably complete for first- and second-generation inbreds of three of the species covered in the literature review (Norway spruce, Douglas-fir, and Japanese black pine), and it is here extended to western white pine. The record of success and levels of seed production attained in second-generation crossing of these four conifers is reviewed in table 5.

Where the number of second-generation crosses attempted in these four conifers has been adequate, generally there is fair crossing success. From 45 to 100 percent of the crosses produced mature cones, and 25 to 100 percent produced filled seeds.

Filled seed yields per cone have been low in S_2 , S_1 X full-sib, and S_1 backcrosses; fair in S_1 single crosses. Data on germination of second-generation inbreds are scanty, and cover only three of the four species of table 5--*Pinus monticola* only for seed from S_1 backcrosses, and *Picea abies* only for seed from S_2 crosses. Nevertheless, in six tests (41 to 1,821 seed per test), the second-generation inbred seed has germinated well--in the 40 to 80 percent range. For *Pinus monticola*, S_1 seed germinated at the 50 percent level (Bingham and Squillace 1955) and there has been no further dropoff in germination of S_1 backcross seed. This confirms Andersson's (1965) observations that reduction in germination occurred principally in the S_1 seed.

Similarly, survival of second-generation inbreds of Douglas-fir and western white pine appears to be good. Orr-Ewing (1965) showed that first-year survival in those second-generation inbred seed lots having more than 10 seed ranged from 30 to 90 percent, and averaged 65 percent. Between 45 and 80 percent (average 57 percent) of the seedlings in five western white pine S_1 backcross seed lots having more than 10 seed survived 3 years in the nursery. Many of them are now 7 to 8 years old in the field.

Righter (1962), and of course many maize breeders before him, have recognized the "reproductive weakness" of inbred maternal parents. He states that "seed yield per

Table 5.--Female step-like field, seed yield, seed loss, and seed germination data, using a type of pollination bag that may have increased losses (Orr-Ewing, personal communication, 1973).

Type of cross	Species	Crosses attempted	Crosses : S ₁ trees	Parental : S ₁ 's of	Original : parents	Crosses : yielding filled seeds	Crosses : yielding mature cones	Strobilus : loss, pollination : to cone	Strobilus : collection	Percent		Filled seed		Germi- nation
										Percent	Percent	Total : Crosses	: nation	
Percent														
S ₂	<i>Fica alba</i> ¹	5	5	2	3	60.0	4	80.0	--	1.2	205.4	41	3	79.2
	<i>Pseudotsuga menziesii</i> ²	30	23	4	2	90.0	30	100.0	16.5	1.6	40.6	95	8	42.8
	<i>Pinus thunbergiana</i> ³	7	4	3	3	42.8	4	57.1	87.0	5.8	6.1	--	--	--
	<i>Pinus monophylla</i>	9	7	4	6	66.7	7	77.8	68.5	2.5	20.1	--	--	--
S ₁ X full-sib	<i>Pseudotsuga menziesii</i>	2	4	2	2	100.0	2	100.0	53.5	24.4	33.2	171	2	73.3
	<i>Pinus thunbergiana</i>	20	35	3	10	50.0	10	50.0	84.0	7.4	6.6	--	--	--
	<i>Pinus monophylla</i>	22	11	4	11	50.0	16	72.7	74.4	6.2	26.7	--	--	--
	<i>Pseudotsuga menziesii</i>	15	15	3	15	100.0	15	100.0	559.8	6.8	36.0	476	15	58.0
S ₁ back-cross	<i>Pinus thunbergiana</i>	20	20	3	5	25.0	9	45.0	85.2	5.1	3.3	--	--	--
	<i>Pinus monophylla</i>	60	44	14	28	45.0	36	60.0	69.6	12.5	40.4	307	6	51.4
	<i>Pseudotsuga menziesii</i>	25	25	7	24	96.0	25	100.0	530.0	18.2	24.0	1821	23	57.5
	<i>Pinus thunbergiana</i>	5	5	3	0	0.0	1	20.0	91.7	--	--	--	--	--
Single cross	<i>Pseudotsuga menziesii</i>	67	41	14	30	44.8	32	47.8	81.1	16.9	23.9	--	--	--

¹After Anderson 1965.

²After Orr-Ewing 1967 and 1969, amended by Orr-Ewing (personal communication, 1973).

³After Karsuta 1968.

Numbers in parentheses are unclear as to exact numbers, but they are some what less (-) or more (+) than numbers having these signs.

Based on 1962 pollinations only, using a type of pollination bag that may have increased losses (Orr-Ewing, personal communication, 1973).

plant is too low for practical purposes," and explains how reproductive vigor is restored in plants from single and double crossing of two or four inbred lines. Actually the maize breeders also selected among their inbred lines for reproductive vigor, and the same principle can be applied to western white pine and other conifers.

An example of the effect of thus selecting for comparatively high self-fertility can be drawn from our results with western white pine. If we had continued the inbreeding program using only those highly self-fertile parents that yielded 60 or more filled S_1 seed per cone (Bingham and Squillace 1955, table 1), we would have selected seven of the nine S_1 lines in which second-generation inbreeding gave low to fair, but consistent yields of filled S_2 seed (3 to 34 per cone).

The effectiveness of such selection for reproductive vigor is emphasized when, as in table 6, a comparison of second-generation cone and seed yields is made between S_1 trees from a comparatively self-sterile parent (tree 19) and those from comparatively self-fertile parents (trees 25 and 58).

Snyder (1968) shows that in Mississippi slash pine yield of filled seed per cone and germination of S_1 seeds are lower than in most other pines. He also shows (1968 and 1972) that inbreeding depression--measured in height growth reduction--increases in slash pine S_1 trees between the first and fifth years of growth (cf. also Bingham and Squillace 1955, and Barnes 1964, for the same phenomenon, ages 1 to 12 years, observed in western white pine). Nevertheless, Snyder's cones from "self-compatible" parents yielded 2 to 13 filled seed per cone compared to 30+ seed per wind-pollinated cone, and one-third or more of the S_1 seeds germinated.

Snyder (1968) concluded, from the low filled-seed and seedling yields per 100 self-pollinated strobili, from the probable (but unknown) delay in flowering of the S_1 trees, and from apparent indications of a relatively low level of nonadditive variance in most traits of southern pines, that an inbreeding program was neither feasible nor practical for improving most characters of slash pine. His own evidence for the first inbred slash pine generation, however, coupled with evidence from second-generation crossing in four other species in *Pinaceae*, makes these conclusions seem premature. The arguments of Franklin (1969) against inbreeding for improvement of loblolly pine (*Pinus taeda* L.) are much stronger, including unknown effects of probably greater pregerminative selection in inbreds, hypersensitivity of inbreds to environmental stress, the relative difficulty (thus high cost) of maintaining inbreds, and the present disaffection of even the maize breeders with the traditional inbreeding-outcrossing hybrid method.

Despite these problems, continuation of *experimental* inbreeding programs in some conifers seems warranted. Consistent, if small, S_1 and S_2 seed yields, and S_1 plants that fruit within reasonable periods, have been obtained in at least four conifers. Also, experimental efficiency probably could be greatly enhanced through selection of comparatively self-fertile parents for subsequent cycles of inbreeding.

Questions that remain for the inbreeder center on long-term economic and genetic practicability, and on the stability of gains under inbreeding as opposed to outcross breeding. To answer these questions, we need to proceed on an experimental basis toward answering such subordinate questions as: What is the gain from one generation of inbreeding followed immediately by single crossing of selected, vigorous S_1 's? and, Is reproductive vigor of the inbreds restored in these early single-cross lines, so that the double crosses may be produced quickly, economically, and in quantity?

It would seem that gains anywhere near those achieved in maize double crossing would finance such an abbreviated inbreeding program in trees. If growth of single-cross lines from S_1 crossing represents little or no gain from heterosis, and bears no relation to vigor of parental S_1 lines, then it will be time to reconsider the practicality of inbreeding programs in forest trees.

Table 6.--Cone and seed yields following crossings on S_1 trees from comparatively self-sterile and self-fertile parents, western white pine

	Crossing success						
Original		S ₁	S ₁		Half-		
parent		full-	back-	Single	sib		
number	S ₂ 's	sibs	crosses	crosses	out-	crosses	Total
CROSSES ATTEMPTED							
19	1	1	10	9	2		23
25	--	--	11	14	2		27
58	6	19	17	9	1		52
CROSSES YIELDING MATURE CONES							
19	0	0	5	1	0		6
25	--	--	7	9	2		18
58	6	16	11	8	0		41
CROSSES YIELDING FILLED SEED							
19	--	--	0	0	--		0
25	--	--	6	9	2		17
58	5	11	11	7	--		34
FILLED SEED PER CONE, AVERAGE							
19	--	--	0.0	0.0	--		
25	--	--	34.4	37.3	32.5		
58	3.3	9.1	10.1	5.3	--		

SUMMARY

There are no reproductive barriers in western white pine restrictive enough to preclude an inbreeding program. Filled seed yields following second-generation inbreeding are low, but consistent, from a variety of matings. Efficiency of the program can be increased by proceeding only with S_1 lines where S_1 seed yield is relatively high.

Reproductive maturity of western white pine S_1 lines was attained at about 15 to 20 years of age, and the fruiting of S_2 lines may be delayed even more. Meanwhile, because of the length of inbred generations, and because the greatest increment of the increase of homozygosity occurs in the first inbred generation, it seems expedient to begin single crossing among the better S_1 lines immediately. Some success has accompanied similar "early" crossing in maize (cf. Lonnquist and Williams 1967). Performance of these single-cross progenies, and the level to which their reproductive vigor is restored, will be critical information in the decision as to whether we should embark on a practical inbreeding program in western white pine.

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Pinus monticola S₁ seedling mortality, timing and extent of fruiting, seed viability, cone and seed weight are compared for 18 S₁ lines and their outcrossed half-sib lines. No reproductive barriers are restrictive enough to preclude continued inbreeding. Filled seed yields from seed generation inbreeding are low but consistent and large enough to justify continuing an experimental program. Results of experimental single crossing between S₁ lines should guide decision on a practical inbreeding program.

OXFORD: 165.414:174.7:181.521:181.522. KEYWORDS: Inbreeding, Pinus monticola (coniferae), cone initiation, seed production.

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Regeneration of Ponderosa Pine in the Northern Rocky Mountain - Intermountain Region



**Marvin W. Foiles
and James D. Curtis**

USDA Forest Service
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INTERMOUNTAIN FOREST &
RANGE EXPERIMENT STATION
Ogden, Utah 84401

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Marvin W. Foiles and James D. Curtis

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Guthrie, Idaho 83437
Robert W. Harris, Director

The Authors

MARVIN W. FOILES is a Silviculturist at the Intermountain Station's Forestry Sciences Laboratory in Moscow, Idaho. Since joining the Forest Service in 1948, he has been engaged in silvicultural research in the northern Rockies. From 1948 to 1957, he worked in the western white pine project in Spokane, Washington. From 1957 to 1967, he conducted research in the Silviculture of Ponderosa Pine and Interior Douglas-fir project in Boise, Idaho.

JAMES D. CURTIS retired from the Intermountain Station in 1966 as leader of the Silviculture of Ponderosa Pine and Interior Douglas-fir research project in Boise, Idaho. He joined the Intermountain Station staff in 1947. He is a graduate of the University of British Columbia and Harvard University.

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Abstract

Present knowledge of natural and artificial regeneration of ponderosa pine in the northern Rocky Mountain- and Intermountain West is summarized. In this territory, ponderosa pine grows under a wide range of climatic, edaphic, and topographic conditions. Summer drought is a major factor in regeneration; thorough site preparation is therefore necessary to reduce competition. Some regeneration techniques that have been tested in this territory are described. Planting is the most successful method of artificial regeneration; direct seeding is sometimes used. Several cutting methods may provide for natural regeneration and are well applied.

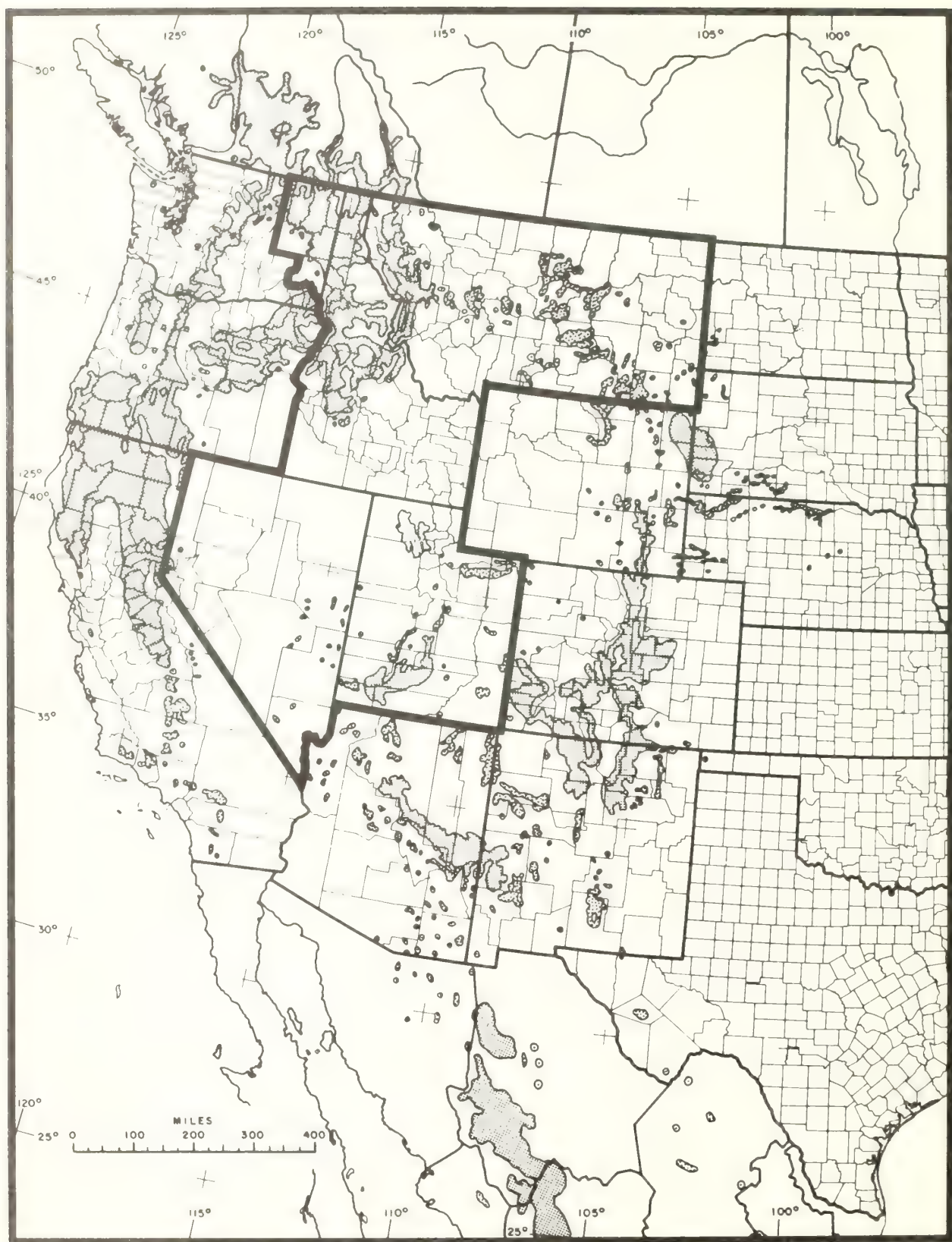


Figure 1.--The northern Rocky Mountain-Intermountain region, outlined with a heavy line, in relation to the total range of ponderosa pine.

Introduction

to reproduce, or regenerate, a forest after a disturbance has removed the old one. The term "regeneration" is quite broad. The result of the process denotes an aggregate of tree seedlings 4.5 feet or less in height that come from natural or artificial seeding, outplanted nursery-grown seedlings, or native stock. More briefly, regeneration consists of groups of trees 4.5 feet in height, regardless of origin.

Regeneration of a forest stand requires the employment of a number of steps. The stand must be adequately stocked with desirable species in a reasonable manner of achieving the desired management plan for the stand. The stand may be managed for one or more uses, such as recreation, watershed management, timber production, or wildlife habitat. Most forest land is managed for multiple uses, and the stand may benefit from a combination of uses. The management objectives may be different, and management for multiple use is more complex. For example, if timber production is the dominant use, the techniques that expose considerable bare soil to hasten the growth of the new stands. If esthetic values and watershed protection are concerns, however, large expanses of bare soil may be undesirable.

Protection of the site is also important. If the site is on erodible soils, slopes are steep, and the weather is severe, it is obviously essential to establish desirable vegetation quickly on cleared sites. The ground must be prepared for regeneration in a way that will prevent erosion. For example, grass seed may be sown to stabilize the soil until tree seedlings are planted after suitable site preparation.

Specific management goals in a regeneration project determine the species and stocking desired in the new stand. Like the management objectives, the requirements become limiting factors in the design of the regeneration plan.

The wide diversity of conditions under which ponderosa pine grows makes a single design of regeneration plan difficult. The plan must be tailored according to the locality and the type of area to be regenerated, such as timber sales, recent burns, or brushfields (old burned areas). On this basis, the choice between natural and artificial regeneration must be made, and an appropriate method of site preparation chosen. Where cutting is yet to be done, a plan should precede the design of the cutting.

Ponderosa pine is the most common tree species in the Pacific Northwest from the Fraser River in British Columbia to the Pacific Coast of the United States (Cartis and Lynch 1963). This species regenerates naturally in only a few places in the United States (fig. 1). The research of some 50 years within an area generally known as the Intermountain region, mostly in Utah, has shown that the species can regenerate naturally in a few places. References to the literature will evaluate regeneration of ponderosa pine in the Pacific Northwest.

Ponderosa Pine in the Northern Rocky Mountain-Intermountain Region

Climate and Soil of the Habitat

Ponderosa pine grows under a wide range of conditions typified by varying rainfall, high temperatures and low humidities during the growing season, mountainous topography, and great diversity of soil types and depth (Curtis and Lynch 1965).

Climate.--In typical ponderosa pine habitats, average annual temperatures vary from 40° F to 48° F and average annual precipitation from 12.7 to 26.8 inches (table 1). The average amount of precipitation from June through September depends on the locality. Idaho City, Idaho, for example, receives one-third more precipitation per year than Darby, Montana, but barely half as much during the June-September period. In southern Utah, the June rainfall is sparse but increases during the following 3 months, almost reversing the pattern of many other places.

In certain places, such as central Idaho, the June-through-August climate is severe. Forest temperature may be 110° F in the shade, relative humidity 3 percent, and total July and August precipitation as little as 0.02 inch.

Most sites are subject in the early or late growing season to soil moisture stress and high soil surface temperatures. Tree growth primarily depends on water stored in the soil from melted snow and from spring rains. Summer precipitation, whether light showers or high-intensity rainstorms, is probably of little use to tree seedlings because of interception, surface evaporation, and runoff. Soil moistures below the wilting point have been measured at a depth of 60 inches in the granitic soils of central Idaho. Soils on south aspects dried out and reached the wilting point sooner than on north aspects.¹

Soil.--From northern Montana to southern Utah there is wide diversity of soil origins and hence soil types. Parent material includes quartzite, argillite, schist, basalt, andesite, granite, limestone, and sandstone. Probably the soils most subject to drought are the coarse-textured, highly erodible granitic types of central Idaho and southwestern Montana. The soils of western Montana on which ponderosa pine is found are the Gray Wooded Great Soil Group (Cox 1957). They are characteristically about 50 inches deep, with a pH of 6 and a "well-developed platy A₂ horizon, a blocky B₂ horizon with a distinct accumulation of clay, and overall gray appearance." The soils developed from argillites and quartzites tend to be shallow and coarse with low water-holding capacity. The medium-textured soils that develop on morainic materials are deeper and their moisture-holding capacity is higher.

¹Unpublished data, Div. Watershed Manage. Res., Intermt. For. & Range Exp. Stn.

Table 1.--Average temperature and precipitation at selected locations in the Intermountain Station territory of the northern Rocky Mountain National Forest.

Location	Average temperature					Average precipitation				
	: June	: July	: Aug.	: Sept.:	: Year:	: June	: July	: Aug.	: Sept.:	: Year
	- - - - - Degrees F - - - - -					- - - - - Inches - - - - -				
Chewelah, Wash.	61	67	64	57	46	1.1	0.6	0.6	1.1	10.8
Spokane, Wash.	62	70	68	61	48	1.5	.4	.4	.8	17.2
Kalispell, Mont.	59	66	63	55	43	2.2	1.0	1.1	1.0	15.4
Missoula, Mont.	58	67	64	54	43	1.9	.8	.7	1.0	12.8
Darby, Mont.	57	65	63	55	45	1.9	.8	.8	1.2	15.7
Grangeville, Idaho	58	67	66	58	46	3.0	.9	.8	1.5	22.6
New Meadows, Idaho	56	63	60	53	41	2.0	.6	.6	1.2	25.3
Council, Idaho	63	73	70	62	48	1.8	.4	.4	.9	26.8
Idaho City, Idaho	58	67	65	57	45	1.4	.3	.3	.6	23.2
Bryce Canyon, Utah	59	63	60	48	40	(¹)	1.1	2.9	3.4	12.7

¹Less than 0.06 inch.

In the Intermountain Station territory there are extensive areas of shallow soil with bedrock often close to the surface. These are frequently intermingled with deeper soils on level plateaus and, more generally, on minor ridges and major drainage boundaries. The total acreage of shallow soils is not known, but surveys on two timber sale areas in central Idaho revealed that the proportion is considerable. On 480 acres on the Boise Basin Experimental Forest supporting ponderosa pine, soil was less than 24 inches deep in 23 percent of the area. On Zena Creek, a tributary of the South Fork of the Salmon River, Payette National Forest, a soil survey showed 31 percent of the area to have soils only 8 to 16 inches deep on bedrock.

Most commonly, the south and west aspects support shallower soils than the north and east aspects. Soil depth generally decreases, regardless of aspect, toward the top of ridges. The deeper soils occur in the ravine bottoms where the topography tends to be gentle, although exceptions occur on some plateaus as in eastern Utah. Cox and others (1960) point out that in western Montana forest productivity is influenced principally by the depth of soil in which tree roots can develop.

Shallow soils affect silvicultural practices (Curtis 1961). For example, certain units may be eliminated from a proposed cutting because soil is not deep enough for adequate site preparation for regeneration or because the potential for erosion or site deterioration following cutting is too great.

¹O. C. Olson. Soils of the Zena Creek logging study, Payette National Forest, Region 4 unpubl. ms., illus. 1960.

Ecological Position and Plant Associations

Ponderosa pine is the most drought tolerant of the major coniferous tree species in the Intermountain Station territory. Therefore, it occupies the relatively warm and dry lower slopes of the Rocky Mountains as they rise above the arid plains. In parts of the territory, such as southern Idaho, Montana, and Utah, open stands of the pinyon-juniper cover type form a transition zone between the prairies and forests in the mountains. In northern Idaho and eastern Washington, however, the boundary between ponderosa pine forests and prairie is abrupt.

In the lowest zone of forest, ponderosa pine is the climax, and the only coniferous species able to survive in that droughty climate. As ponderosa pine extends farther up the moisture-temperature gradient, it becomes a seral tree in stands where more competitive species eventually become climax.

Daubenmire and Daubenmire (1968) classified the forest vegetation of eastern Washington and northern Idaho into ecological units termed habitat types. Ponderosa pine occurs as a climax or seral species in 11 of their habitat types, listed below in approximate order from most warm and dry to most cool and moist.

Pinus ponderosa/Stipa comata
Pinus ponderosa/Agropyron spicatum
Pinus ponderosa/Festuca idahoensis
Pinus ponderosa/Purshia tridentata
Pinus ponderosa/Symphoricarpos albus
Pinus ponderosa/Physocarpus malvaceus
Pseudotsuga menziesii/Symphoricarpos albus
Pseudotsuga menziesii/Calamagrostis rubescens
Pseudotsuga menziesii/Calamagrostis rubescens, Arctostaphylos phase
Pseudotsuga menziesii/Physocarpus malvaceus
Abies grandis/Pachistima myrsinites

In the first six habitat types in the list, ponderosa pine is the climax dominant. In the last five types it may be a temporary invader following burning or logging, but it is replaced as the climax dominant by Douglas-fir or grand fir. Ponderosa pine grows rapidly where it is seral if light is sufficient. In an understory position, it cannot compete with the climax species and is eventually eliminated from the stand. In the past, wildfires were largely responsible for maintaining ponderosa pine in mixed stands by creating bare areas in which the pine could become established and compete favorably with the slower-growing climax species. In recent years, logging and burning of clearcut patches have created bare areas.

Ponderosa pine is rated very resistant to ground fire, second only to western larch among the coniferous species of the northern Rocky Mountains (Flint 1925). This rating applies to old trees with thick bark, but small trees are easily killed by ground fires.

Planning for Regeneration

In all regeneration planning, the basic choice lies between natural and artificial regeneration. With ponderosa pine, management objectives and the characteristics of the location and site determine this choice. With either method, however, site preparation is usually necessary for seed germination and seedling survival.

Natural Versus Artificial Regeneration

Both natural and artificial regeneration have evident advantages and disadvantages. Planting permits initial control of composition and stocking, a distinct advantage, but requires a considerable investment. When stands are to be clearcut and planted, logging is more straightforward than when seed trees must be retained on the cutting area. On planted areas there is no delay before regeneration begins and the chance of early success is more certain than if natural regeneration is relied on, although without good planning there is some danger of an inappropriate seed source.

Natural regeneration, though often economical, is less reliable, and the retained seed trees must be cut and removed after reproduction is established. The seed trees help to ameliorate a harsh climate, however, and are esthetically pleasing. The ultimate choice between artificial and natural regeneration will be decided by such local and specific factors as the presence and location of seed trees, amount of available seed, availability of planting stock raised from seed collected on the tract or nearby, size and topography of area, soil and site, silvical requirements of the species, condition of trees in the overstory, and costs.

With artificial regeneration of ponderosa pine, the time schedule for the reproduction period is easier to determine and is much shorter than with natural regeneration. Primarily, natural regeneration is limited by the occurrence of an adequate cone crop. Therefore, a time objective must be long enough to include a heavy seed year. A reasonable objective for natural regeneration would be one-tenth of the rotation or the occurrence of one adequate cone crop. If natural regeneration fails to become established in that time, the site should be planted. With careful planning for seed collection and nursery production a timber sale area can be planted within a year. A reasonable objective would be 5 years following the cutting.

Another limitation is the availability of seed from a proper seed source. In natural regeneration there is no problem, providing that desirable seed trees have been selected, because the seed comes from on or near the site. For direct seeding or planting, however, seed must be collected within genetically approved horizontal distances and elevations to ensure that the trees will be adaptable to the site.

Seedling survival is a key factor in regeneration in these mountainous areas because the cost of repeated treatments is high. If the initial attempt at natural or artificial regeneration fails, rapid reinvasion of the site by brush and steep slopes make the second effort difficult and the total investment high.



Figure 2.--Because vegetation was not completely eliminated, competition has reinvaded this plot 1 year after stripping by bulldozer.

Site Preparation and Treatment

When regeneration, either natural or artificial, is to be established, some kind of site preparation is usually necessary, to remove competition and expose mineral soil. Evaporation is slower from mineral soil than from forest duff. The better moisture relations of mineral soil make it a better medium for pine seed germination and seedling survival (Roe and Squillace 1950).

Throughout the growing season, plants of all kinds draw moisture from varying depths of the soil. The wilting point is often exceeded at depths down to 2 feet in vegetated soils. In availability of moisture, the first year is the most critical period for the tree seedling. Upper soil layers dry quickly and first-year roots may not grow fast enough to reach lower moisture supplies. Although the vertical penetration of roots of 1-year natural ponderosa pine seedlings is known in extreme cases to reach 51 inches, they are found more commonly at the 16- to 20-inch depth (Curtis and Lynch 1965). The removal of competing vegetation makes moisture available for tree seedlings and increases the survival of natural regeneration and outplanted nursery stock (Foiles and Curtis 1965b; Curtis and Coonrod 1961).

On areas needing regeneration the competing vegetation may consist of grasses, sedges, forbs, and shrubs. Forest soils also contain seeds which germinate when the site has been disturbed (Curtis 1952). As many as 948,736 viable seeds per acre of forbs, grasses, sedges, and shrubs have been recovered from the topsoil in the ponderosa pine type of central Idaho (Krygier 1955). When the vegetation on a site is removed and the top few inches of soil are pushed aside there is less competition than if only the existing vegetation is removed. The thoroughness with which live vegetation and seed in the mineral soil are eliminated from a site will determine the rate of reinvasion from seed and from sprouting root systems (fig. 2). Removing part

of the topsoil from a large area would be incompatible with the aim of protecting the soil from erosion and preserving site productivity. Nevertheless, some soil can be moved from spots, strips, or trenches without seriously damaging the site. Probably the fibrous-rooted species of grasses, forbs, and sedges provide more competition (Spence 1937) than shrubs (Baker and Korstian 1931), if density of root systems and the depths to which they penetrate are criteria.

Rather drastic site preparation methods have been developed in recent years, out of the need to solve some of the problems of regenerating ponderosa pine stands. For example, attempts to plant ponderosa pine in central Idaho and Utah had failed for nearly 30 years before the Town Creek Planting Study was begun in 1954. Results from that study showed that thorough site preparation (bulldozer stripping), combined with careful planting, brought success. In the years following the Town Creek Study, the method of dozer stripping and planting was employed to reforest thousands of acres of land covered with brushfields resulting from wildfires. Without that treatment, those productive timber-growing sites would have remained unproductive for many years. Such drastic methods as dozer stripping or terracing are neither desirable nor necessary in all situations, however. They are discussed here to show their value where they are desirable.

The use of chemicals and fire has also been criticized and sometimes restricted in recent years because of the dangers of environmental pollution. Forest managers must weigh the advantages and disadvantages of these methods in relation to the overall management objectives for the forest. If chemicals or fire endanger high-priority values of the land, other methods of site preparation can be used. The method should be chosen long before the time arrives to prepare the site, because the choice may affect earlier management decisions, such as the selection of a cutting method.

Scalping and mulching.--On steep slopes where it is impossible for machinery to work safely and efficiently, ground must be prepared by hand, fire, or chemicals. In hand preparation, a pit (basin) or scalp can be formed on the sidehill (fig. 3). When a pit is made, the tree or seed is planted slightly to one side of the center to avoid being covered by soil sloughing from above. Scalps may vary in size according to the amount of competing vegetation but should be at least 30 inches in diameter.

Mulching, like scalping, has been used to preserve moisture by reducing evaporation from the soil and by limiting the growth of competing vegetation around planted trees. Straw, sheets of 4-mil black polyethylene, and mats of glass fiber 1/4-inch thick were applied to scalped spots 3 feet square on steep slopes in central Idaho to observe the benefits of mulches (fig. 4). Four tests over a 3-year period were indecisive in terms of survival of planted trees. Generally, seedlings on scalped and mulched spots survived no better than on spots that were only scalped (Hall 1971).

DeByle (1969) significantly increased survival of planted Jeffrey pine in Nevada by mulching with 3- by 3-foot sheets of 4-mil black polyethylene. His test was similar to the central Idaho experiment using the same material to mulch planted ponderosa pine. The contrasting results from these experiments indicate that the effectiveness of mulching cannot be generalized. More information is needed on the effects of mulches under different conditions.

Herbicides.--The reduction and elimination of vegetative competition by chemicals before planting have been frequently tested by foresters in recent years. Perhaps the most common use has been in brushfields where vegetation has invaded forest stands



Figure 3.--A shallow layer of soil was removed from this scalp to eliminate seeds as well as roots of competing vegetation.

Figure 4.--A glass fiber mulch 3 feet square is held in place by heavy wire pins and stones.



after uncontrolled fires (fig. 5). Both woody species and herbaceous found in brushfields; the species composition will vary by location. Since all plant species are not affected to the same degree when any one herbicide is used, more than one chemical may be required. In central Idaho³ satisfactory results have been obtained with aerial applications of 2,4,5-T and dalapon applied in 2 years at the rate of 8 gallons of spray per acre. Concentration dosages were equivalent (a.e.) of 2,4,5-T and 20 pounds of dalapon in 1 gallon of diesel oil and 6 gallons of water. Another area sprayed with 3 pounds a.e. of 2,4,5-T and 20 pounds of dalapon in 1 gallon of diesel oil produced satisfactory kill of shrub vegetation. Handsprayed areas with more dilute solutions (4 pounds a.e. of 2,4,5-T and 20 pounds of dalapon in 200 gallons of water) gave equally good results. The solutions contained 100 ppm of diesel oil. The solutions successfully reduced competition from grasses and sedges on the site.

Other herbicides have been used successfully on brush species in the northern Rockies (Potter 1968, Ryker 1966). New herbicides are being discovered and developed rapidly and will increase the flexibility and usefulness of chemical treatments. Foresters can use chemicals to prepare sites for regeneration, but they should choose the chemicals carefully and recognize their limitations. For example, herbicides that successfully kill growing vegetation may not kill plants that grow from seed in the soil after spraying. Chemical sterilants or preemergence phytocides may control germinating weed seeds, but residual chemical in the soil may be toxic to tree seedlings if they are planted too soon. Herbicides can be valuable tools if the right chemical is used according to tested procedures. Foresters need to be aware of current developments in order to make effective use of chemical site preparation.



Figure 1.--Aerial application of herbicide to brushfield on site of uncontrolled fire.

Fire.--Burning is a common method of disposing of slash from logging operations. Slash may be piled, or burned where it fell. Disposal of slash and accumulated unmerchantable material makes the area more accessible to planting or seeding crews and usually reduces plant competition to a degree that allows planted trees to survive. Burned areas, however, are rapidly invaded by plants, either from seed in the soil or by sprouting from surviving root systems.

The seed of some species of forest shrubs such as *Ceanothus velutinus* have impermeable seed coats and remain dormant until exposed and warmed by fire. Therefore, fire can actually result in prolific germination of old seed stored in the soil (U.S. Forest Service 1948; Curtis 1952). As many as 72,745 viable *Ceanothus velutinus* seed per acre have been found in the top soil layer of the ponderosa pine type (Krygier 1955). A combination of fire and spraying with herbicides may be necessary to prepare such sites adequately for pine regeneration.

Mechanical techniques.--On gentle slopes, where machines can operate safely, mechanical site preparation can be efficient and economical (Gordon 1956; Curtis 1964). Toothed land-clearing blades (fig. 6), bulldozer blades, and disks, mounted on the front of tractors, as well as disks or plows mounted on the rear, have all been used successfully in Intermountain Station territory. On sale areas where clearcuts are made and slash is dozer-piled and burned, planting is sometimes successful without further site modification, although plowing in addition usually results in higher survival.

In brushfields, tractors with angle dozer blades can be used to prepare sites by stripping or terracing, depending on the steepness of slope. Stripping can be used on slopes of less than 40 percent gradient. By this technique, vegetation is pushed from a strip the width of the dozer blade. Angling the dozer blade removes only enough soil to eliminate the vegetation (fig. 7). To minimize the possible erosion hazard, the strips are made parallel to the slope contour, and a band of vegetated ground is left undisturbed as a barrier to soil movement between strips. Rows of trees are then planted in the prepared strips.

On slopes steeper than 40 percent gradient, tractors cannot safely traverse the slope and do the stripping unless a terrace is constructed. The degree to which such structures approach the level varies in actual practice. Sometimes a trail is constructed for the uphill track of the tractor only, and the surface of the terrace slopes down toward the outside. This type of construction is common in shallow, rocky soils where a deep cut may remove too much soil to retain a productive site. On other sites the terraces may be level or slanted inward to catch more precipitation and ameliorate the harsh microclimate.

Site preparation can be accomplished on fairly steep ground by use of a small tractor equipped with a reversible double disk plow and hydraulic vertical lift. This machine will make a single furrow about 12 inches deep and 24 inches wide on ground up to about 40 percent slope. The furrow slice is cut by one disk and cast downhill by the second disk. A tree-planting machine can then ride nearly level with one wheel on each side of the furrow.

Mechanical site preparation should be completed in the summer preceding the year of planting. Then, most soil settling and sloughing will have occurred by the time trees are planted and stock is less likely to be buried. Site preparation by tractors is more efficient when the ground is bare of snow, the soil is below field capacity, and weather is conducive to efficient working conditions.



Figure 6.--To prepare a site for natural regeneration, this tractor, equipped with a land-clearing blade, is scarifying along contours in a group selection cutting.

Figure 7.--To prepare this site for planting in a central Idaho brushfield, parallel contour strips are made by a tractor with a bulldozer blade. Two rows of trees are planted on each strip.



Artificial Regeneration

Artificial regeneration by seeding or planting has been tried experimentally since the beginning of the 20th century in the regions being discussed here. In the northern Rocky Mountains large-scale planting and seeding projects were started to reforest extensive areas denuded by the destructive fires of 1910. Planting of ponderosa pine was largely successful; artificial seeding was nearly always unsuccessful. Planting became the dependable and established method of starting new forest crops (Wahlenberg 1925). In spite of many failures in these early trials, direct seeding has always appealed to foresters because the procedures appear to be simple and inexpensive, and to provide a method of regenerating large areas in a short period of time. Later, more intensive experiments helped define the conditions under which seeding can succeed (Schopmeyer and Helmers 1947). Seeding has never been used extensively, however, and planting has continued to be the most common method of artificial regeneration.

In the Intermountain area seeding and planting trials were started later than in the northern Rocky Mountains, and the results were different. Both seeding and planting were considered failures in early experiments in central Idaho and Utah, and tests continued into the early 1940's without success. In 1954 a reappraisal of past planting trials led to the establishment of the Town Creek planting study in central Idaho (Curtis and Coonrod 1961). This large-scale test led to the conclusion that thorough and adequate site preparation and careful handling and planting of the nursery stock were essential to high survival of ponderosa pine. Since the Town Creek study, planting has become an established method of regenerating brushfields and timber sale areas on the National Forests of the Intermountain Region. Although some acres are seeded nearly every year, direct seeding has not been used on an operational scale.

Seed Source

Selection of a proper seed source is an important first step in any reforestation project. Ponderosa pine seed source studies have confirmed the long-held belief that the local seed source is best (Weidman 1939, Squillace and Silen 1962). Native trees growing on or near the regeneration site are most likely to be adjusted to the climate, soils, and other environmental factors.

Elevation of the seed source has been shown to be important in site choice within the local area. On sites where planting stock came from seed sources at various elevations, trees from elevations similar to the planting site have proven superior in the long run (Callahan 1960). The superiority of similar-elevation sources shows up in growth rate, form, and adaptation to environmental hazards such as temperature and moisture extreme. Latitudinal distance from the planting site is also important, but limitations have not been determined closely. Very likely, some site characteristics such as aspect are as important as horizontal distances, but their importance has not been proven. If local seed collection zones have not been determined, seeds should be collected from stands in the same habitat type, within 500 feet vertically, and as near as possible to the area to be regenerated. Initial survival is no indication of later thriftiness. Trees and stands from distant seed sources may survive and grow well for a time, only to be killed or severely damaged by an extreme local climatic condition such as cold or heat (Kempff 1928, Squillace and Silen 1962), or to decline in vigor as they grow older.

The characteristics of individual seed trees deserve attention. Parent trees that will produce genetically superior progeny cannot always be selected by visual observation. There are guides, however, which suggest some general things to look for in selecting superior trees (U.S. Forest Service 1957). Seed trees should be collected from the better-than-average trees in the stand and from better-than-average stands.

To provide a more abundant and regular seed supply from a known source of good genetic quality, seed production areas have been developed. They are selected to provide seed for a particular area or zone, with a special reference to elevation. On each one, the most vigorous and well-formed trees of an existing stand are released to a spacing of about 30 feet and treated to promote seed production. The effects of spacing, irrigation, fertilization, cultivation, and insect control on seed production need to be determined. The most promising measures will be used to promote seed production in these stands.

Eventually, some seed for direct seeding and nurseries will come from orchards of selected trees that have demonstrated ability to produce progeny with specific genetic characteristics we value. Desirable characteristics might include resistance to some disease or insect, increased growth rate, improved wood quality, drought resistance, or improved cone quality for esthetic uses such as Christmas trees. The characteristics desired may vary with ownership and locality.

Seed Production and Storage

Ponderosa pine is a variable producer of seed, and heavy cone crops occur infrequently (Curtis and Lynch 1965). In western Montana, only one "good" crop and five "fair" crops were recorded in 23 years of observations (Boe 1954). In central Idaho, three very heavy cone crops were reported from 1935 through 1958 (Curtis and Foiles 1961).

Ponderosa pine trees produce large numbers of cones and seeds in years of heavy crops (fig. 8). For example, cone yields from the very heavy crop of 1936 in central Idaho (table 2) averaged from 222 cones per tree on immature trees to 1,409 cones per tree on mature scattered trees. Seed yields from the same crop averaged from 16,100 seeds per immature tree to 118,300 seeds per mature tree (U.S. Forest Service, Intermountain Forest and Range Exp. Stn. 1937).

The reasons for the variability of seed crops are not fully known, but some observations and measurements have been made. In a northern Idaho study, pollen dispersal was greatly reduced in years when rains fell during the pollination period (Turner 1956). The amount of seed killed by cone and seed insects can be extremely high in some years (Keen 1958). A surprising number of birds and small mammals also consume seed before it falls to the ground (Curtis 1948). Such losses are important in years of light or medium seed production. Squirrels (*Sciurus* spp.), chipmunks (*Tamias* spp.), and mice (*Peromyscus* spp.) are unquestionably responsible for the greatest losses in seed, both from the tree and after dissemination. In western Montana and in central Idaho, mice, chipmunks, or shrews (*Sorex* spp.) destroyed over 90 percent of fallen ponderosa pine seed (Adams 1950; Foiles and Curtis 1965b; Schmidt and Turner 1971). In another study in western Montana squirrels not only destroyed 85 percent of the cone crop, but by the nature of their clipping, destroyed the current year's seed, the 1-year-old conelets, and the flowering potential of the trees from which cones were clipped (Squillace 1953; Adams 1955; Schmidt and Shearer 1971). It was concluded from these studies that squirrels can harvest most seed in light and medium seed years, thus minimizing the chances of adequate seed establishment. Prevention of cone losses from standing trees by repellents to repel squirrels and so protect a supply of genetically desirable seed production in western Montana (Tackle 1959).



Figure 8.--Branch ends of ponderosa pine trees are heavily laden with cones during years of heavy seed crops.

Table 2.--Mean yields of ponderosa pine cones and seeds from a very heavy crop, 1936, in central Idaho¹

Tree	: :Altitude: Feet	: :Age : Years	:Cones per: : tree	:Cones per: : bushel	:Seeds per: : cone	:Seeds per: : tree	:Fanned seed : per pound
Immature, stand	4,000	46	300	302	64	19,700	8,575
Immature, stand	5,500	38	222	251	77	16,100	8,050
Immature, isolated	4,000	42	586	267	80	43,000	8,200
Immature, isolated	5,500	36	368	281	74	24,500	8,450
Mature, scattered	4,500	150+	1,407	268	71	101,000	8,350
Mature, scattered	5,500	150+	1,409	227	92	118,300	8,875

¹From Annual Investigative Report 1936-37, U.S. For. Serv., Intermt. For. & Range Exp. Stn.

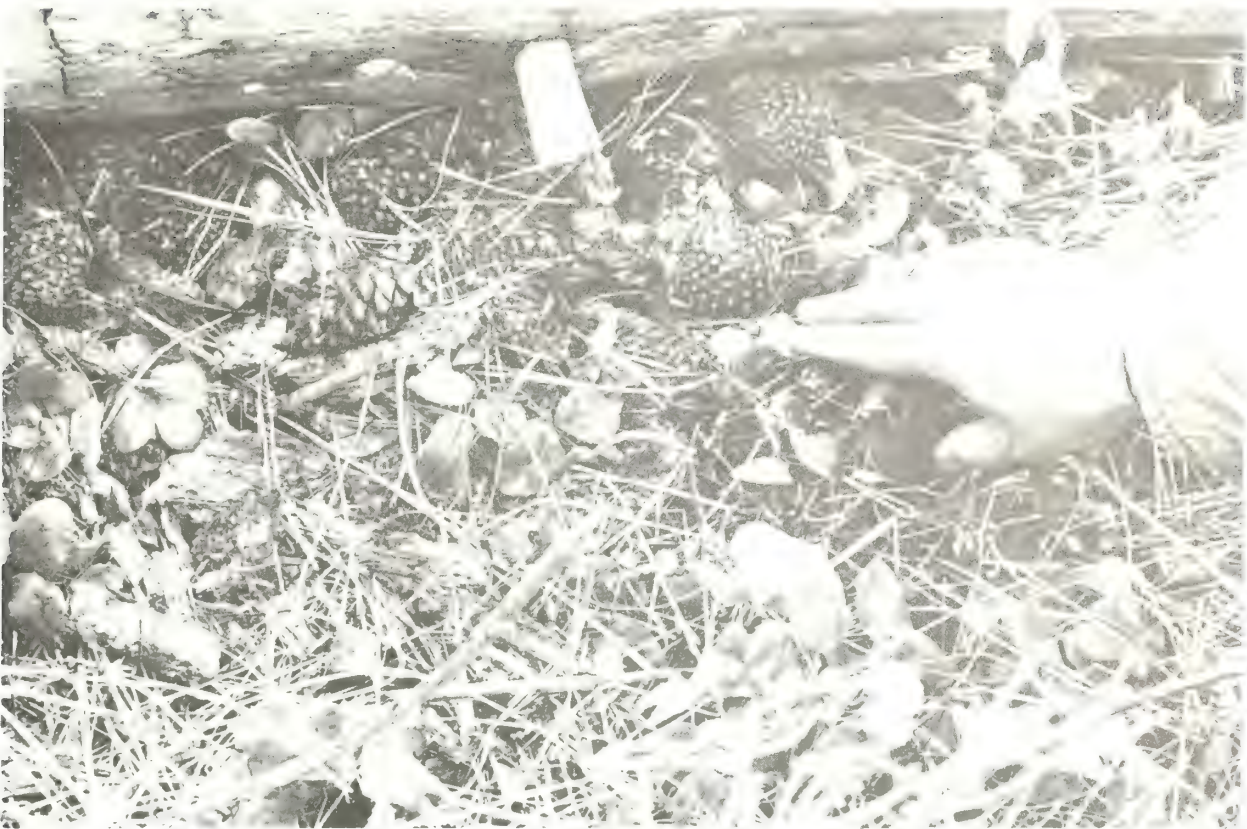


Figure 9.--*Animal holes of rodents in seed orchards are numerous, but the parent trees cannot be identified.*

Attempts employing repellents to prevent small rodents and birds from consuming freshly fallen seed have been unsuccessful in central Idaho (Foiles and Curtis 1965b). Rodent eradication was successful in Oregon but required three distributions of poisoned bait (Stein 1964). In California, five patch cuttings, ranging in size from 7 to 800 acres, were baited prior to direct seeding in 1964 and 1965 (Hall 1967). In that experiment 175 acres were baited, including buffer zones, to protect 84.5 acres of seeded area. When total costs were applied to the seeded area, labor costs averaged \$1.55 per acre and bait \$0.67 per acre--a total of \$2.22 per acre. Birds, especially grouse, can be a source of disfigurement and mortality to young natural stands and plantations, but such damage is not severe or widespread (Sparhawk 1918; Curtis and Foiles 1964). A study in western Montana measured the progress of mortality during the entire cone development period (Shearer and Schmidt 1970). Three-fourths of the potential crop aborted or failed to develop because of some undetermined factors. Grouse reduced the crop an additional 14 percent, and insects and miscellaneous other factors destroyed another 5 percent. Only 6 percent of the potential cones completed their development and disseminated seeds.

Seed collection.--Picking cones from trees can be a difficult task. Cones are most abundant near the top of the crown and at branch ends, where they are difficult to reach. They can be collected from squirrel caches on the ground, although their genetic quality is then unknown (fig. 9). Sometimes cones can be collected conveniently from felled trees on areas that are being logged. If seed orchards and seed production areas are on nearly level ground, truck-mounted mechanical hoists may be an economical method of reaching cones quickly and safely.

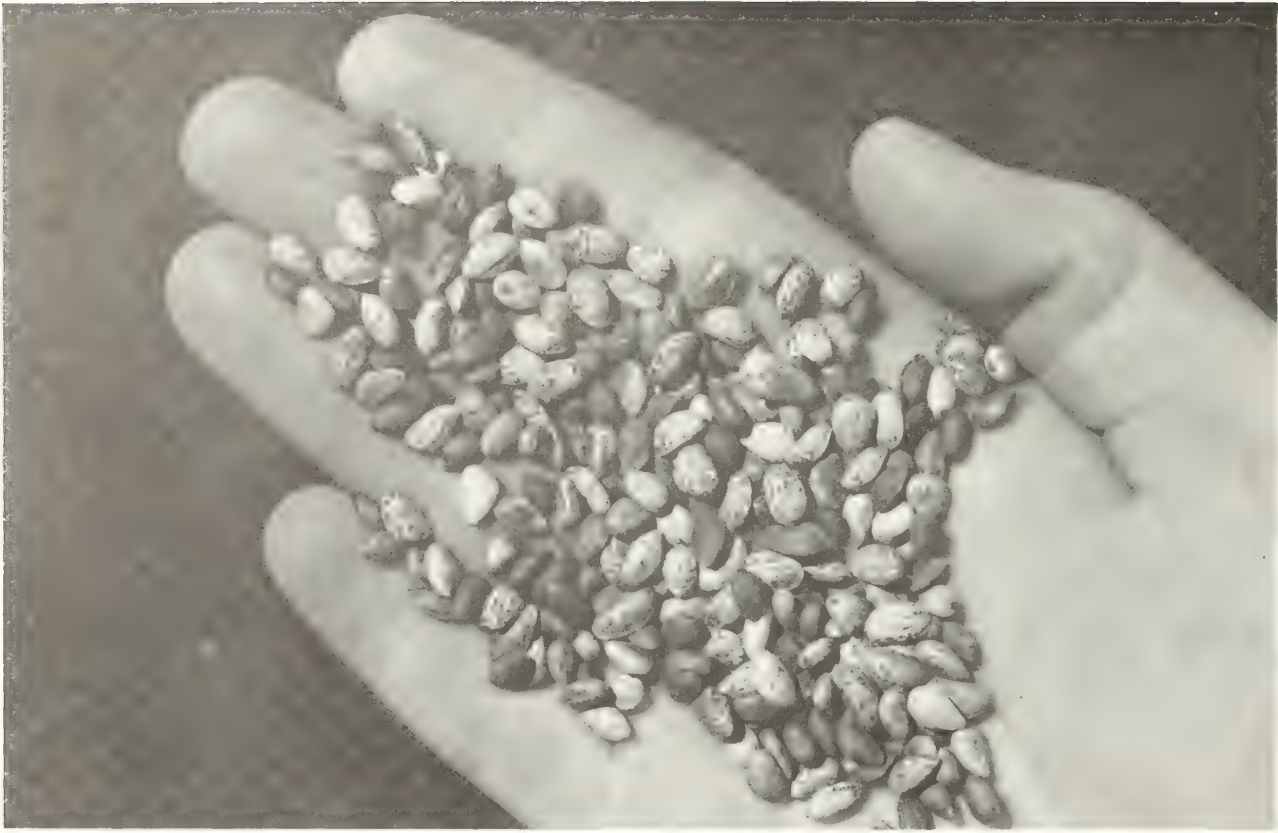


Figure 10.--These typical ponderosa pine seeds are from a very heavy seed crop in central Idaho.

Ripe cones have a specific gravity of 0.80 to 0.86 in central Idaho (Maki 1940). The degree of ripeness can be tested by dropping closed cones into kerosene or a half-and-half mixture of kerosene and raw linseed oil. When most of the cones from a tree float, the seeds from that tree are ripe. The float test should be applied only to freshly picked cones.

Seed storage.--The infrequency and irregularity of ponderosa pine seed crops make seed storage necessary in a program of artificial regeneration. Fortunately, very heavy cone crops generally produce high percentages of good seed (fig. 10), which can be stored for use during intervening years.

Ponderosa pine seeds have been stored successfully for 14 years when dried to less than 10 percent moisture content and placed in sealed containers at a constant temperature near 32° F (Curtis 1955b). Other workers (Allen 1957, Barton 1954, Schubert 1955) have reported successful storage at temperatures from 32° F to 0° F, although temperatures near 32° F were the best.

Direct Seeding

Direct seeding has never been used extensively in the northern Rockies although some areas are seeded nearly every year. Summaries of the results of extensive early tests report many failures and a few successes (Wahlenberg 1925; Maki 1938). Contributing factors in most successes were believed to be thorough elimination of competition and favorable weather patterns (Wahlenberg 1925). Many of the early seedings were attempted on very dry sites where planting had failed previously. The knowledge gained

from summaries of previous tests was used in a series of direct seeding trials in northern Idaho and western Montana during the period 1937 to 1940 (Schopmeyer and Helmers 1947). Results show that with effective protection from animals ponderosa pine can be seed-spotted successfully on favorable sites that have been recently and severely burned (Helmers 1946).

The two major difficulties in direct seeding are animals and the harsh environmental forces (Wagg and Hermann 1962). Hand-sown seed and the seedlings germinating from them suffer from the same agents of first-year mortality as naturally sown and seedlings. Planting, on the other hand, partially overcomes these destructive agencies.

Ground preparation.--Any of the methods described in the section on site preparation can successfully reduce competition, but for direct seeding a method that mineral soil should be chosen because pine seeds germinate best in that medium. Cultivating or loosening the soil on the spots before sowing increased germination in one test (Loewenstein and Pitkin 1966) and had no appreciable effect in another test (Schopmeyer and Helmers 1947) in northern Idaho.

Sowing rates.--In early seeding studies the tendency was to sow large number seeds to insure establishing some seedlings. For example, 20 to 25 seeds were sown per spot, and this often resulted in spots with many seedlings in close competition. Some foresters believed the excessive numbers of seedlings necessitated thinning to prevent stagnation, loss of growth, or the development of poorly formed trees (Stein 1957; Wagar and Myers 1958). One northern Idaho study showed that the number of seedlings per spot significantly affected both diameter and height growth of dominant ponderosa pine trees for 17 years after spot seeding (Foiles 1961). Although a satisfactory stand developed without thinning, sparsely stocked plots had a notable growth advantage.

In recent years, a trend toward reduced sowing rates reflects greater experience with direct seeding and a preference for lower initial stocking in reproduction stands. Most management guides now recommend 400 to 500 established seedlings per acre. Sowing rates should be based on the ratio of the number of viable seeds sown to the number of established seedlings at some predetermined age. Unfortunately, the seed-to-seedling ratio is not easy to predict. It varies by sites and is affected by site preparation, seed viability, weather in a particular year, seed protection measures, and other factors. Tests of seeding on different sites are needed to develop seed-to-seedling ratios for sowing guides and to help determine which sites can be seeded economically. Until results are known, the germinative capacity of individual seed lots will help determine sowing rates.

Season of sowing.--Pine seeds are usually sown in the fall (Wahlenberg 1925; Schopmeyer and Helmers 1947). Fall-sown seed is stratified naturally over winter and is ready to germinate early in the spring. Spring sowing is often delayed because the planting sites are inaccessible until mountains become passable. If seed can be sown early enough, however, spring sowing does have an advantage over fall sowing; protection from rodents and birds is shorter time.

Protection.--Various methods of protecting planted seeds from rodents and birds have been tried (Wahlenberg 1925; Schopmeyer and Helmers 1947; Maki⁴). In experimental seedings, losses to rodents have been reduced effectively by placing screen cones over seed spots, but the screening method is too expensive for general

⁴T. E. Maki. Artificial seeding of tree species in the Intermountain Intermt. For. & Range Exp. Stn., Moscow, Idaho. File rep., 45 p. 19

Baiting the area with poison grain and sowing repellent-coated tree seeds have had considerable success. Many poisons and rodenticides have been tested in various parts of the United States with varying effects, but none has worked consistently enough to be universally accepted. In recent years, the most commonly used treatment has been to bait the area with poison grain and then sow seeds coated with a combination of the poison endrin, a fungicide thiram, and a bird repellent aluminum powder in a latex carrier.

When need for rodent control is anticipated, the advice and cooperation of a professional control organization, such as the Predatory Animal and Rodent Control division of the Fish and Wildlife Service, should be sought. Control officers can advise on methods of estimating the kinds and relative numbers of seed-eating mammals on the area to be treated. When the population survey is completed, they can assist foresters to secure recommended baits and poisons, and can supply instructions on treatment and safety precautions for handling and distributing the poisons. The use of many chemicals has been restricted because of danger to other than target animals. Before any chemical is used, assurance should be secured that it is currently registered and approved for the specific purpose anticipated.

Planting

Planting is the most commonly used method of artificial reforestation in both Intermountain and northern Rocky Mountain forests. Nearly 45,000 acres were planted in 1970. Hand planting is the usual method, although machines are used successfully. In recent years an increasing share of the site preparation and planting has been awarded to private contractors who hire the crews and complete the job to written specifications.

Nursery stock production.--The production of healthy stock from nurseries is essential to reforestation by planting. Stock must be in condition to grow when it is outplanted. Causes of past failures include insufficient site preparation and careless handling and planting of stock. At present, nurseries in the Intermountain Station territory are producing suitable and healthy ponderosa pine stock, as confirmed by the high survival rates of recent plantings.

Even though forest nursery tree production techniques are satisfactory, greater efficiency would be achieved through better methods of seed treatment and nursery bed weeding. More precise studies of fertilization and irrigation schedules and seedbed spacing should improve stock production and vigor. In the long run, probably the greatest benefits will come from basic studies of seed and seedling physiology and genetics. Recent studies in California have led to development of methods of determining the root-regenerating potential (RRP) of nursery stock and how it varies with different nurseries and nursery practices (Stone and Schubert 1959a and b; Schubert and Baron 1965; Stone and others 1963).

The main requirement for good ponderosa pine nursery stock is a healthy root system 10 to 12 inches long (Curtis and Coonrod 1961). If such stock is well planted, the roots have a chance to stay ahead of the receding soil moisture level during the dry summer months. The roots should be in balance with a healthy top; a root-top ratio of 1.5:1 or 2:1 is desirable.

The most common age of planting stock used in these regions in recent years has been 2+0 seedling stock. Most of the earlier plantings used some form of transplant stock ranging from 1+1 to 2+2, but a 1954-58 study showed that 2+0 plants survived nearly as well as 2+1 stock on well-prepared sites (Curtis and Coonrod 1961). Fifth-year survival of 5 successive years of planting averaged 82 percent with 2+0 stock and 94 percent with 2+1 stock on stripped and trenched sites. The lower survival rate of 2+0 stock is compensated for by the lower cost of producing and planting seedlings as

compared to transplant stock. Recently, tests of planting 1+0 seedlings have been made. Nurserymen believe they can grow 1+0 ponderosa pine stock suitable for planting, especially on well-prepared sites.

Raising seedlings in inexpensive containers and then outplanting both the seedling and container is a method being either tested or used successfully in several forested regions (Jones 1967; Kudrjavcev 1965; Williamson 1964). Planting containers or tubes of various materials, sizes, and shapes are being tested. Advantages claimed for this system include minimizing production time, cost, and initial planting shock; prolonging the planting season; and increasing survival on certain sites. Commonly the tubelings are planted in the field 6 to 8 weeks after seed germination. At that stage of growth, the roots have not reached the bottom of the container, so root growth is not interrupted during outplanting.

Container planting was tested in central Idaho as a means of increasing survival on dry sites (Curtis and Foiles 1964). Sixteen kinds of containers, 10 to 18 inches long and made of several different materials, were planted on various sites and in two seasons, spring and fall. Seedlings were grown in the tubes for 1 and 2 years before outplanting, rather than for 6 to 8 weeks. Relatively long containers were used to minimize root competition and to provide the taproot with a better chance of remaining in moist soil. Container planting did not improve survival under the conditions tested in central Idaho. Possibly some other form of container planting will prove advantageous in the future, but for the present, survival of bare-rooted stock is satisfactory.

Stock lifting and storage.--In California, date of lifting and length of time in storage strongly affect the root-regenerating potential of outplanted stock (Stone and Schubert 1959b). The optimum time for lifting and storing stock needs to be determined for each forest nursery in the Intermountain Station territory. Usually, ponderosa pine stock is lifted in early spring and stored at near-freezing temperatures for periods of a few days to 8 or 10 weeks with carefully controlled humidity. This schedule agrees with Stone and Schubert's recommendations from California for timing the lifting and planting operations to take advantage of the period of peak root growth in the spring.

Stock shipment and field storage.--The best method of packing and shipping nursery stock depends on weather conditions, distance, and time in transit. The stock must be protected from heating within bundles and from excessive drying by sun and wind. Roots will die after a few minutes of exposure to dry air. Furthermore, the right combination of heat and moisture in bundles can prompt the breaking of dormancy, which can be as fatal to seedlings as excessive heat.

It is seldom possible to plant trees the same day they are delivered from the nursery; therefore, some kind of field storage is necessary. In the past, most stock was heeled-in on the planting site and taken out as needed for immediate planting. In recent years, however, that method has been largely replaced by cold storage accessible to the planting site.

Heeling-in consists of storing the stock in trenches with the tops exposed and the roots covered with tightly packed damp soil. If this method must be used, at remote planting sites, storage should be for as brief a time as possible, in damp, shaded soil. After more than a few days, warm weather is liable to cause the plants to break dormancy and start growth; then disturbance is a greater shock than the original lifting and storage. Lifting trees after growth has started may interrupt root growth and delay root initiation after outplanting.

Bundles of trees can be stored in cold storage plants if these are available near the planting site. Temperature of 33° to 40° F and humidity of 90 to 99 percent is desirable, with free air circulation through the room.

Storage in snow has proven successful and convenient for most planting projects in the Intermountain Region (Curtis and Coonrod 1961). The trees, still packed in nursery bundles, are buried in snow; sometimes snow is collected and placed in small sheds constructed for tree storage at a central location such as a Ranger station, but more often snowbanks along roads at higher elevations than the planting site are used. Each day enough trees for the day's planting are transported to the planting site and kept in snow inside a tent. The trees are sorted, graded, and placed in planting bags inside a tent. This procedure minimizes the exposure of planting stock to drying from heat and wind before it is planted.

Field planting.--Shallow soils make planting difficult because some soil must be removed in preparing the site, and too little may remain. If the site is prepared by stripping, plowing, or furrowing with tractors, 18 inches or more of soil may be displaced. On steep slopes where manual labor replaces machines in the site preparation and planting process, the 8- to 12-inch roots of the planting stock require at least 18 inches of soil to survive and grow. Therefore, it is inadvisable to plant sites having less than 24 inches of soil.

Ponderosa pine plantings have been attempted in both spring and fall. Earlier research suggested that early spring was generally the best season for planting in this region (Schopmeyer 1940). In recent years, however, both fall and spring plantings have been successful under certain circumstances. Fall planting has been recommended for high elevation sites where the trees are protected by an early snow cover. Deep snow also makes these sites inaccessible during the early spring planting season. Ponderosa pine is most often planted on low elevation sites, however. These are accessible in early spring and do not receive a protective snow cover until late in the fall. Therefore, ponderosa pine is usually planted as early as possible in the spring.

Several different hand planting tools have been used, including shovels, mattocks, planting bars, modified one-hand mattocks, and backpack power-driven augers. These tools have given satisfactory survival when good stock was planted on well-prepared sites and the recommended planting technique was carefully followed. The kind of soil and its stoniness, steepness of slope, kind and amount of site preparation required, and custom all influence choice of planting tool. Detailed descriptions of the precise technique for each tool are available in textbooks and manuals (Toumey and Korstian 1942; Lynch 1952; Corson and Fowells 1952). With any method, a little extra care in planting can easily increase survival 10 to 20 percent (Cushman and Weidman 1937).

In Intermountain forests, planting on contour strips is common. In this method, an influential factor is the spacing pattern of trees on the strips, which may be 30 feet or more apart on slopes up to 60 percent. The usual practice is to plant two rows of trees about 3 feet apart on the strip, with 8-foot spacing of trees in staggered rows. There is danger that trees in this spacing pattern may grow much like open-grown trees, at least on one side, thus reducing wood quality. Group plantings on the strips can possibly improve the quality of at least some trees, which could be favored as crop trees. The effects of different spacing patterns on growth and yield and quality of trees planted on bulldozed contour strips need further study.

Where the ground is prepared by terracing, some soil is displaced from the inside of the terrace to the outside, thus creating a range of soil conditions across the terrace. Trees can be planted on the inside of the terrace near the cutbank, in the middle of the prepared surface, or on the outside in the fill soils. Nursery stock and potted seedlings were planted in three rows on the inside, middle, and outside of terraces in central Idaho to determine the most favorable position (Curtis and Foiles 1964). Survival of trees was significantly highest on the inside of the terrace, intermediate on the middle, and lowest on the outside of the terrace where the loose fill soil dried rapidly.



Figure 11. This ponderosa pine plantation on Latah Plateau, Idaho, was planted in furrows.

The range of soil conditions across a terrace affects height growth as well as survival of planted trees. Analyses of planting tests conducted over 5 years showed that trees planted near the cutbank were significantly taller than trees near the outside of the terrace 10 years after planting (Hall and Curtis 1970).

Towed planting machines have been used in Intermountain forests with good results on prepared ground and on moderate slopes (fig. 11). A crew consists of three men: the tractor operator, a planter on the machine, and a followup man who walks behind the machine to inspect the planted trees and correct any faulty planting, especially incomplete tamping. The planter and the followup man alternate jobs.

Survival of machine-planted ponderosa pine has been high for the few years that this method has been used. It was compared with hand planting in one test in central Idaho in 1960. Four 10-acre plots had been aerially sprayed with herbicides to eliminate the brush competition. Half of each plot was hand planted without further site preparation and half was furrowed and machine planted. Two-year survival on the machine planted plots averaged 77 percent on east aspects and 71 percent on west aspects. Survival on hand-planted plots averaged 17 percent on east aspects and 6 percent on west aspects. The poor survival on the hand-planted plots was attributed to a rapid invasion of cheatgrass (*Bromus tectorum*) after the brush was killed. Furrowing removed the cheatgrass seeds from the machine-planted trees. Although the comparison was not conclusive because of poor survival on the hand-planted plots, machine planting was successful, and many acres elsewhere planted by machines have shown survival as good or better than in this test. Since 1962, private planting contractors have relied on hand planting because it requires no investment for equipment and because machines are restricted to gentler slopes.

Machine planting has several advantages over hand planting:

1. More consistent quality of planting. Every tree is planted in the same way.
2. High rate of production. The machines used in the Intermountain Region planted 4,000 to 8,000 trees per 8-hour shift and the machines could be run for two shifts a day, especially important when the planting season is short.
3. Lower overhead costs.

Some disadvantages of machines include:

1. Limitations of slope. They cannot work ground steeper than about 40 percent.
2. Dependence on machines. If the tractor or planting machine breaks down mechanically, the whole crew loses time.
3. The high cost of purchasing specialized machinery that is used only a few weeks each year.

Planting machines will be more useful in mountain country when a machine is developed that can work on contours on slopes steeper than 40 percent. Also, machines need to be better adapted for work in rocky and log-strewn areas.

Natural Regeneration

Characteristic of ponderosa pine forests is the obvious presence of advance reproduction. Seedlings may occur singly or in small or large groups, depending on conditions at the time of their establishment. Advance reproduction is mentioned in ponderosa pine literature as occurring in "waves," interpreted to mean that although small numbers of seedlings may occur from year to year, they are established at irregular and unpredictable intervals in considerable abundance and over areas of several hundred thousand acres or more. This phenomenon of a wave of natural seedling establishment, aided by higher than usual moisture and cool temperatures, occurred in central Idaho in 1963 (Foiles and Curtis 1965a), the first instance since 1941. The classic example, in Arizona in 1919, was the only one during a 38-year period between 1908 and 1945 (Pearson 1950).

The presence of some established advance reproduction may give the impression that considerable numbers of seedlings are established almost annually. Unfortunately, successful coincidences of ample germinable seed and favorable growing conditions cannot be relied on because they cannot be effectively predicted. If, however, a heavy seed crop is in evidence, the forester may consider several logging methods that provide for natural regeneration in different ways. When advance reproduction is present, carefully planned harvest cutting is needed to protect the young stand from excessive logging damage.

Seed Dissemination

Whatever the reproduction cutting method, seed must be disseminated from trees near or near the area to be regenerated. The precise time that seed will be disseminated and the distance that it will travel from seed trees vary widely. Weather at the time of seed maturation and dissemination, heights and positions of seed trees, topography and altitude of the location, nature and duration of the air turbulence during dissemination, and degree of cone persistence all affect the time, place, and quantity of seed fall. In a central Idaho bumper crop, 254,000 seed per acre fell in virgin forest, 203,000 per acre in a selectively cut stand (with residual volume of 1,047 board feet per acre), and 243,000 per acre in a 70-year-old second-growth stand (U.S. Forest Service, Intermountain Forest and Range Exp. Stn. 1937). In western Montana, ponderosa pine seed reached the ground at the rate of 104,000 per acre in a selectively cut stand with residual pine volume of 4,760 board feet per acre (Squillace and Adams 1950).



Figure 12.--A seed tree cutting in a western Montana ponderosa pine stand.



Figure 13.--A shelterwood cutting followed by ground scarification resulted in adequate ponderosa pine regeneration.

Reproduction Cutting Methods

Clearcutting.--Seed production and seedling survival records enable the forester to estimate the size of cone crop needed to attain a reasonable goal of 1,000 seedlings per acre. A test in small clearcuts in central Idaho determined the ratio of seed to established seedlings to be 55:1 on scarified soil in weather somewhat warmer and drier than normal (Foiles and Curtis 1965b). Under these conditions an adequate seedfall would be 55,000 seeds per acre in the center of the clearcut openings. In Oregon, a study of seed dissemination into a clearcut from the edge of an uncut stand showed that seedfall 2 chains from the timber edge was only about one-fourth as much as seedfall under the timber (Barrett 1966). Therefore, the margin of a timber stand must produce at least 250,000 seeds per acre to result in the required 55,000 seeds 2 chains from the timber. Only a very heavy cone crop produces this seedfall (Foiles and Curtis 1965a, Barrett 1966); only such a crop, therefore, can be considered adequate to regenerate small clearcut openings in one year. In bumper crop years, dominant trees 40 years old and older are heavily laden with cones, obvious even to the casual observer. Not all sites are regenerated in one year, however. In areas with favorable climatic conditions, several medium cone crops over a period of 3 to 6 years might be as good as one bumper crop.

On clearcuts, then, the longer dimension should be at right angles to the prevailing wind and the shorter dimension should not be more than 260 feet as a maximum width; 200-foot widths would be preferable for better assurance of adequate seed distribution.

Of course, clearcuts can be larger if a combination of natural and artificial regeneration methods is used. Natural regeneration may be planned for a distance of about 130 feet from the timbered edges; the remaining interior of the tract can be planted or seeded artificially.

Seed-tree and shelterwood.--Both seed-tree and shelterwood cuttings remove only a part of the stand; the remaining trees are cut after the reproduction is established. Though insuring a supply of seed, the two cutting methods have the disadvantage of subsequent reproduction losses from logging the residual stand. Dominant, vigorous seed trees should be selected for either the seed-tree or shelterwood system. Such trees, if they are free of disease, are likely to be good seed producers and resistant to wind and other damaging agents.

Seed-tree and shelterwood cuttings have been used successfully by private industry and on the National Forests in western Montana and northern Idaho (figs. 12, 13). Seedfall and reproduction resulting from one trial of these methods were measured in southern Idaho. Two L-shaped areas on the Boise Basin Experimental Forest at Idaho City, totaling about 10 acres, were chosen prior to the very heavy seed crop of 1958. Each area contained an east and a south aspect. One area was scarified by a land-clearing blade, the other by 12 disks, 36 inches in diameter; both devices were front-mounted on a D-7 tractor. Both areas supported deep and shallow soils and 90-year-old ponderosa pine singly and in groups. These areas resembled seed-tree and shelterwood cuttings only on a limited scale, but nevertheless provided interesting comparisons of first-year seedfall, seedling numbers, and stocking 3 years after dissemination (table 3).

For natural regeneration on cutting areas wider than 260 feet, with reproduction density that will provide adequate stocking after 3 years, the seed-tree method rather than clearcutting should be used. Assuming the seed trees are mature (over 150 years old), the number needed will depend on the seed yield. At the 55:1 ratio of seed to established seedlings, two or three spaced trees per acre are required for full regeneration of the area if a heavy crop of seed (100,000 per tree) can be predicted.

Table 3.--*Density of seed dissemination, established seedlings, and stocking per acre 3 years after dissemination for seed-tree and shelterwood plots on the Boise Basin Experimental Forest, 1958*

	Seed-tree plot				Shelterwood plot			
	Seed	Seedlings	Stocking	Seeds	Seed	Seedlings	Stocking	Seeds
Scarifying tool	per acre	per acre	percent ¹	per seedling	per acre	per acre	percent	per seedling
Land-clearing blade	202,000	3,476	87	58	255,000	4,690	90	54
Disks	33,120	304	42	109	172,560	1,360	72	127

¹Stocking percent = percent of 4-milacre quadrats containing at least one seedling.

that 8 to 12 dominant trees 16 to 24 inches dbh will provide enough seed for regeneration in an average seed year. Reserving this larger number of trees also makes subsequent logging of the seed trees more economical.

Single-tree and group selection.--The selection method (otherwise called selective cuttings, or selection logging, partial cutting) has been employed in the West and in the Intermountain Station territory more commonly to cut ponderosa pine than any other method. Unfortunately, the selection method is subject to a wide variety of interpretations. Textbooks describe the selection method as harvesting the oldest or largest trees in a stand at repeated intervals throughout the rotation (Hawley and Smith 1954). The objectives of the cuttings are to create uneven-aged stands and to regenerate such stands. Most selective cuttings in ponderosa pine forests were not designed to meet fully the objectives of the selection method; rather, they were planned to remove individual trees or small groups selected on the basis of one of several criteria including tree vigor, susceptibility to insect attack, and economic value. Although application of selection cutting has varied, the values of the method have been seen as twofold. First, it was a compromise between clearcutting and leaving the stand untouched, maintaining reserve volume as growing stock that would provide high net increment per acre in the residual stand. Second, the reserve trees would provide a seed source, a reservoir for the future. As an added advantage, the method demonstrates to the public that foresters are not stripping cover from watersheds and ruining the beauty of the countryside. A real disadvantage is, however, that unless the cutting is designed with skill and understanding, the result can be the high-grading of a stand, so that it consists of low-quality trees after cutting.

Some ponderosa pine stands appear to be all aged. Usually these consist of two or three separate age classes, but include all crown classes because trees have developed unevenly over a long period of time. Selection management with a long rotation is possible in these stands if the early cuttings are made carefully to develop the size classes needed for future cutting cycles. A rotation of 160 to 200 years is necessary because both tree growth and regeneration are slower under these conditions. Natural reproduction is established only by an infrequent good seed crop followed by a growing season with favorable weather. The selection system has the advantage of maintaining a continuous stand of timber that is esthetically pleasing and protects the sites.

Because early single-tree selection cuttings varied in purpose and execution, they are difficult to evaluate. Reproduction establishment was greater after cutting than before in one of these early cuttings in western Montana (Boe 1948); volume of the



Figure 14.--Seedfall from a heavy cone crop averaged 245,240 ponderosa pine seeds per acre and ranged from 123,320 to 345,080 per acre. In addition to the pine, an average of 1,200 white pine seeds per acre were also collected.

reserve stands did not greatly influence levels of reproduction or stocking 35 years after cutting. In contrast, later cuttings in central Idaho showed a decrease in density of reproduction over a 15-year period following cutting, although stocking remained dense (Wilson 1951). A 1932 study of cuttings made between 1906 and 1924 on the Boise National Forest showed a striking deficiency in establishment of postlogging reproduction except where 26 years had elapsed since cutting (Curtis 1950).

As more information became available from research, the kinds or types of trees removed in these stemwise selection cuttings changed (Keen 1943). The *Dendroctonus* bark beetles were found over great areas of the West to be the most important cause of mortality in mature and overmature stands, and marking systems were devised so that those trees considered to be the highest risk were removed in the first cutting (Keen 1943; Salman and Bongberg 1942). Silviculturally speaking these were actually sanitation cuttings, but the effect of their removal was similar to that of single-tree selection cuttings.

The group-selection method is adaptable to a wide variety of ponderosa pine stand conditions. Mature trees are removed in groups or patches instead of singly, and the openings thus created provide conditions satisfactory for regeneration in an even-aged structure. In addition to being satisfactory for timber growth, group selection may improve other forest values such as wildlife habitat, water production, and esthetic quality. The openings vary in size but are usually small enough to become stocked naturally.

In central Idaho the rate and amount of reproduction was studied on scarified areas within openings created by group-selection cutting (Foiles and Curtis 1950) (fig. 14). Seedfall from a heavy cone crop averaged 245,240 ponderosa pine seeds per acre and ranged from 123,320 to 345,080 per acre. In addition to the pine, an average

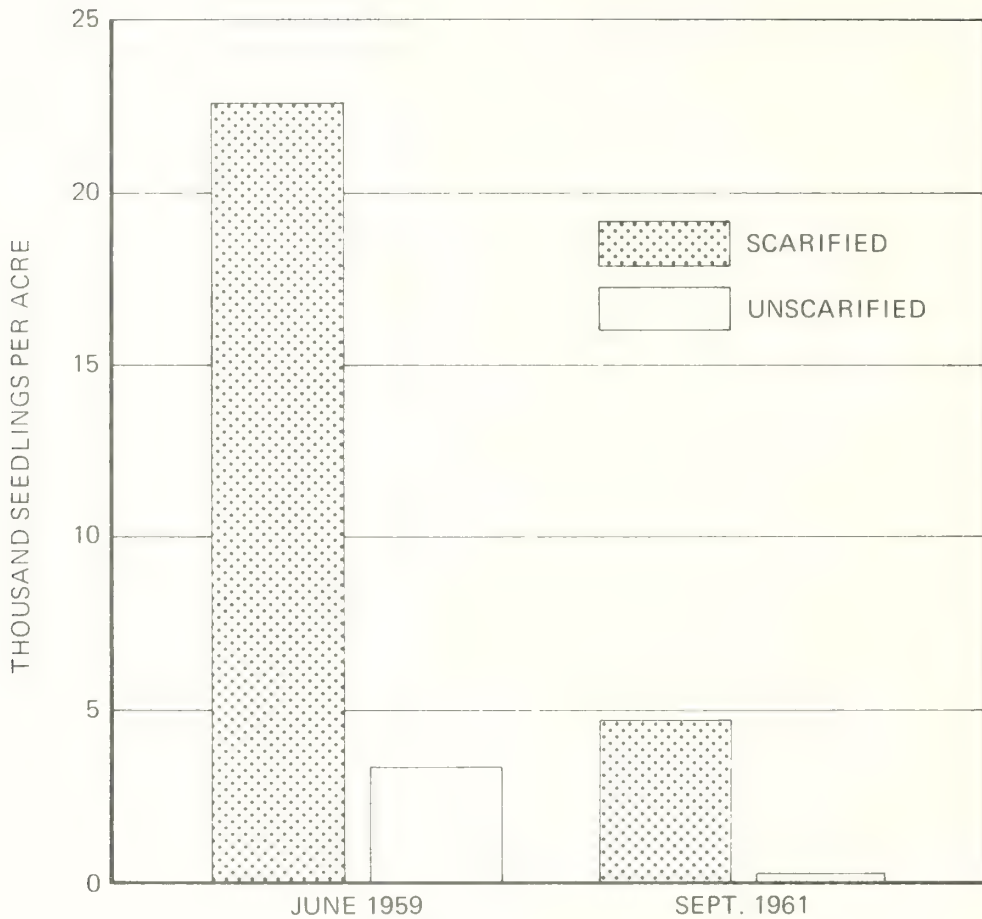


Figure 15.--Many more seedlings per acre were produced on scarified than on unscarified sites following a very heavy seed crop.

of 49,720 Douglas-fir seeds per acre fell in the openings. Even with this amount of seed per acre and near-average growing season weather, some areas were below acceptable stocking (40 percent of milacres stocked) 3 years later. The number of seedlings that germinated was significantly different on scarified and unscarified ground (fig. 15). Germination was poor on unscarified sites, even though large amounts of seed were present; the scarified areas averaged more than 22,000 germinates per acre (fig. 16). During the ensuing 3 years, however, mortality reduced the average number of seedlings on scarified sites to about 4,700 per acre in the fall of 1961.

On scarified ground, the degree of stocking after 3 years varied by aspect. The stocking on ridges and on southwest slopes (from S. 45° E. to N. 45° W.) was lower than on northeast slopes (from N. 45° W. to S. 45° E.) (fig. 17). Mortality reduced the stocking on all three of these sites between June 1959 and September 1961. On ridges and on southwest slopes, stocking was irregular and unreliable as compared to northeast slopes, where all adequately scarified sites were acceptably stocked (40 percent of milacres). These data illustrate that for prompt establishment of ponderosa pine reproduction there must be site preparation as well as an adequate source of seed. Results also suggest that some method of regeneration other than clearcutting may be preferable on sites with southern or western exposure and shallow soils.



Figure 10.--Close-up of pine cone lying on the ground in a sampled part of a slash pine stand in 1959.

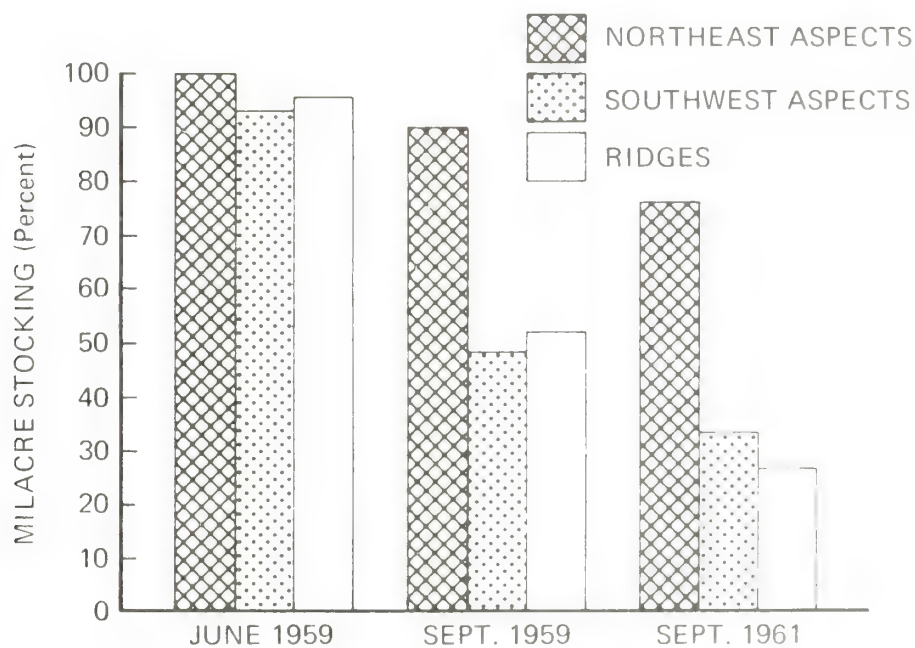


Figure 11.--Loss of slash pine seedlings in a sampled part of a slash pine stand in 1959.

Application of Cutting Methods to Habitat Types

The 11 habitat types in which ponderosa pine occurs differ in the relative severity of the regeneration problem under each of the reproduction cutting methods. Which method to prescribe for a particular habitat must be decided by considering the economic consequences in relation to the silvicultural results. The following discussion is limited to an evaluation of the silvicultural aspects of regenerating forest stands in the various habitats.

Climax Position

The four habitat types in which ponderosa pine is associated with *Festuca*, *Agropyron*, or *Stipa* grasses, or a combination of *Purshia* shrubs and these grasses, have similar characteristics and present similar problems of timber management. They are on the dry and warm end of the moisture-temperature gradient for tree growth, ponderosa pine is the climax tree vegetation, and pine stands are often infected with dwarf-mistletoe. In these stands dwarfmistletoe is a prime consideration. The only known practical way to prevent infection in the new stand is to eliminate the source--the infected trees--and clearcutting, with seeding or planting, is the most practical method of doing it. Other cutting methods could eliminate the sources of infection if it was not heavy.

If dwarfmistletoe is absent a wider selection of cutting methods is available. All of the high-forest methods of reproduction have been used in these stands with some success. Ponderosa pine is the only tree species present; so competition with other species is not a consideration. Natural regeneration is often sporadic and difficult to obtain, however, because of the hot, dry site, competition from grasses for what soil moisture is available, and the infrequency of good seed crops. Clear-cutting and planting produce the quickest and fastest timber growth if they are compatible with the overall management objectives of the area. The site is thoroughly prepared for planting to reduce competition from grasses sufficiently to insure adequate survival of the planted trees.

Group selection, seed-tree, or shelterwood methods, if properly executed, can be applied to stands on these habitat types. Care must be taken to develop the desired age classes. Such cuttings produce enough seed for regeneration, but the competitive grass cover may increase following cutting. Therefore, the site must be prepared shortly before a good seed crop occurs. Then the new crop should be released in a few years by removal or reduction of the seed-tree or shelterwood overstory. Careful logging is required to avoid excessive damage to the reproduction stand.

The *Pinus ponderosa* and *Pinus jeffreyi* habitat types are the most representative of the six types in which ponderosa pine is the climax tree. Dwarfmistletoe, a threat in the drier types, is absent in these two. Inconsistency of seed production and droughty summers are difficulties shared with the pine-grass habitat types. Undergrowth dominated by brush species is a problem not encountered in the grass-dominated associations. The brush cover discourages regeneration in two ways. It is a physical deterrent during planting and competes with young seedlings for water and nutrients. Burning removes the physical obstacle temporarily, but these species regenerate promptly from subterranean organs and dormant seeds in the soil surface. Therefore, mechanical site preparation that removes the brush and exposes mineral soil for a longer time is necessary for planting or prompt natural regeneration.

Clearcutting is the most appropriate reproduction cutting method if timber production is the primary goal. It alleviates the problem of undergrowth of brush, the primary difficulty in reproducing pine in these types. On a clearcut, mechanical site preparation is easier, either by itself or used with fire or chemicals, and thorough site preparation is essential to prompt regeneration. In addition, clearcutting allows trees in the new stand to grow where they grow best--in the open.

Seed-tree and shelterwood systems are successful if properly applied. The stand should be prepared, exposing mineral soil, shortly before seedfall from a good cone crop. Once established, trees in the young stand will survive and grow satisfactorily for at least 20 to 30 years, so immediate removal of the overstory is not necessary. Growth of the young trees will be faster, however, if the overhead shade is removed.

Selection management with a long rotation is possible under the conditions recommended for the ponderosa pine-grass habitat types. That is, cuttings should be carefully designed to develop age classes needed for the future. Selection management should be used only when the primary objective is to maintain a continuous stand of timber for an esthetic environment or for site protection, and timber production is only a secondary objective.

Seral Position

Ponderosa pine loses its position as a climax species when moisture becomes adequate for Douglas-fir to reproduce successfully. Then ponderosa pine becomes a seral tree in a series of habitat types in which Douglas-fir is the climax species. The *Douglas-fir-pseudotsuga* and *Douglas-fir-ponderosa* types have characteristics similar to the associations of ponderosa pine with the same shrub unions. The choice of cutting methods for ponderosa pine in these stands is complicated somewhat by the presence of other tree species with different silvical requirements and disease and insect problems.

Douglas-fir, western larch, and lodgepole pine are common associates of ponderosa pine in Douglas-fir habitat types. Douglas-fir is the most shade-tolerant species in this group, western larch and lodgepole pine are intolerant species, and ponderosa pine is intermediate in tolerance. Therefore, silvically, each species is favored by different methods of cutting.

The choice of method depends largely on the species to be featured in management of the stand. In turn, the choice of species is strongly influenced by disease and insect problems that commonly arise in these habitat types. Dwarfmistletoe infections are severe and frequent in Douglas-fir, western larch, and lodgepole pine, but they do not attack ponderosa pine on these habitats. Spruce budworm (*Pectinophora gossypiella*) commonly attacks Douglas-fir and occasionally western larch. Larch casebearer (*Coleophora laricella*) severely defoliates western larch throughout the region. In addition, bark beetles sometimes cause extensive mortality in Douglas-fir, ponderosa

pine, and lodgepole pine. A particular disease or insect may dictate the choice of cutting methods. Generally, managers try to maintain a mixture of tree species so that no one pest will destroy the entire stand.

Clearcutting followed by planting insures a mixture of species in the stand; it both protects the stand from disease and promotes growth. Where disease and insects are not major problems, any of the high-forest cutting methods are possible, depending on the management objectives. Single-tree selection cuttings promote the natural succession toward pure Douglas-fir, the most shade-tolerant species. Ponderosa pine germinates and survives for 30 to 40 years in the shade, but eventually it ceases to reproduce and is eliminated from the stand. Therefore, the manager should not use single-tree selection cutting if he intends to keep ponderosa pine in the stand.

Group selection, seed-tree, or shelterwood cuttings can provide for stands of mixed species composition. Group selection cutting creates small openings of 0.25 to 2 acres in which all four species will regenerate and grow well following adequate site preparation. Seed-tree and shelterwood cuttings require additional treatments to encourage seed germination. Then the seed trees should be removed shortly after the reproduction stand becomes established to promote growth of pine and larch seedlings.

Ponderosa pine grows best on sites of the *Abies grandis*-*Pachistima myrsinites* habitat type. Natural reproduction is less sporadic and more dependable than in the drier pine habitats. It will not persist, however, unless satisfactory conditions are present, particularly freedom from overhead shade. Grand fir and Douglas-fir are more competitive than ponderosa pine on these moist sites, and in dense stands they eventually overtop and eliminate pine from the stand. Therefore, cutting methods must provide sufficient light for ponderosa pine. In addition, stands of this type are often subject to serious damage from insects and diseases. Both grand fir and Douglas-fir are attacked by spruce budworm, for example. Grand fir is very susceptible to heart-rot fungi that weaken the trees in addition to destroying much of the wood. The impact of these diseases and insects becomes greater with advancing age of the stand. Under these circumstances, management systems, such as single-tree selection, which lengthen the rotation and increase the proportion of shade-tolerant species, may encourage insects and diseases. Even-aged management of these stands through shorter rotations leads to healthier and more productive forests, with conditions that allow ponderosa pine to form a valuable component of the stand.

As in other habitats, clearcutting and planting create the desired conditions for ponderosa pine most simply. It is important that the planted trees be from a seed source within this habitat type. Again, group selection and seed-tree methods can be successful if they are properly executed.

This evaluation of reproduction cutting methods in various habitat types is based partly on observation of actual practice but largely on the silvical requirements of ponderosa pine. All the cutting methods have been tested in the territory discussed here, though not under all conditions. There is still a need to explore the effects of the various methods in terms of values other than production of timber.

Regeneration Development and Protection

When is a seedling established? This question is difficult to answer. From the time forest tree seed reaches the ground, either in the nursery or in the forest, until the tree is harvested, natural forces work against its survival. Disease, insects, birds, mammals, cold, heat, snow, hail, shade, too much water, too little water, wind, and fire, directly or indirectly, can kill trees of different ages. The first few years of a tree's life are probably the most critical. Until the young tree has had several years to develop its crown and root system, its chance for survival is precarious. A seedling is never established in the strict sense of the word, but we can decide on a time when, for practical purposes, a seedling can be considered so.

The loss of seedlings in the first 3 years after germination or after planting probably represents a greater rate of loss in stems per acre than at any time in the life of a ponderosa pine stand, except for episodes of fire and epidemics (Meyer 1961; Korstian and Baker 1925; Pearson 1950; Tackle and Roy 1953; Foiles and Curtis 1965a). The most important causes of mortality in these first 3 years are drought, insolation, animals, and damping-off and other fungal diseases (Curtis and Coonrod 1961; Foiles and Curtis 1965a). After 3 years the seedlings are stronger and less susceptible to some of these agents. Then others such as higher mammals, insects, diseases of roots and foliage, competing plants, and weather become more prominent (Meyer 1961; Wilson 1952; Adams 1951a,b; Dingle 1956). Because of the rather abrupt change in mortality rate at this time, we may consider a tree seedling established 3 years after the seed has germinated or the seedling or transplant has been outplanted on the forest site.

Losses During Establishment

Drought is the chief cause of seedling loss during the period of establishment. In a large-scale study where 90 acres were planted each year for 5 years and where three classes of stock were planted on three differently prepared sites, drought was believed the principal cause of mortality each year (Curtis and Coonrod 1961). In a 3-year study of natural reproduction establishment, drought and insolation together accounted for 64 percent of total mortality of 1-year seedlings (Foiles and Curtis

1965b). Many times during late June, July, and August, on south and west aspects, mineral soil surface temperatures exceed 152° F, considered potentially lethal to very young seedlings (Baker 1929). Soil moisture measured at 6-, 12-, and 18-inch depths in a mulching study showed that beneath weed-free surfaces on south- and west-facing slopes the wilting point was commonly exceeded at depths to which tree seedling roots penetrated. The moisture deficiency accounted for mortality of some outplanted stock (Hall 1971).

Additional causes of mortality of natural seedlings less than 3 years old are fungi, cutworms, birds, rodents, deer, hail, washing, and burying by eroding soil. Damping-off is frequently responsible for extensive mortality in newly emerged seedlings (Foiles and Curtis 1965b), but is virtually impossible to control under forest conditions. In plantations, apart from drought, animals--hares, gophers, and porcupines--probably account for most losses during the first 3 years, but are commonly sporadic in their attacks.

Losses After Establishment

Logging.--Ponderosa pine advance growth occurs to some extent in nearly all stands of the species. Because reproduction is so difficult to establish, damage to it must be avoided. Some stand damage from logging is inescapable, but planning can lessen the degree of understocking caused by it (Mowat 1940; Curtis 1955a; Barrett 1960). High intensity of cut can result in significantly lower stocking of advance reproduction after logging. On an 838-acre experimental cutting in central Idaho, tractor size, cutting method, and initial volumes varying from 10,000 to 20,000 board feet per acre produced no differences in initial and postlogging stocking, but heavy cutting caused significantly greater damage to the understory than light cutting (Foiles 1962).

Damage to young stands by logging can be reduced by (1) felling trees up or down slopes on areas to be logged by jammer and angled to skid trails in areas to be cat skidded; (2) felling a group of trees in one direction and, if possible, in one place; (3) skidding logs by tractors at right angles to contours and down ridges wherever feasible; and (4) removing all limbs on large trees before skidding to avoid raking, bending, and breaking of seedlings and saplings. The number of chokers should be limited to from three to five, depending on the size of the logs, to prevent the load from fanning, making an unnecessarily wide skid trail, and skinning tree bases. To see that these practices are observed, enlisting the interest of the woods boss and crews in management objectives is far superior to relying on supervision. This approach is more educational and enduring in its effects.

Fire.--Fires are a constant threat to any forest stand. Even fast-moving surface fires can wipe out the youngest age classes completely (Connaughton 1936). They occur frequently and are difficult to control in the ponderosa pine type. Fortunately, State, federal, and private fire control organizations are prepared for these annual emergencies with revised fire plans and the latest equipment. Management plans for reproduction stands should include fire protection.

Disease.--Diseases are potential agents of severe damage to young trees and stands. Diseases that cause only occasional damage under ordinary circumstances may cause widespread destruction under certain favorable conditions. Dwarfmistletoe is often prevalent on certain habitat types, but it can be controlled silviculturally with available guidelines (Boyce 1961; Childs 1963; Leaphart 1963). Root-infecting fungi such as *Fomes annosus* and *Armillaria mellea* cause both mortality and growth loss in young pines. Most root diseases spread from the stumps of cut trees into adjacent stands; therefore, these diseases may become more widespread with increasing application of thinnings. *Ellytroderma* needle cast causes considerable damage locally, and is occasionally widespread on ponderosa pine. Unknown pathogens have been suspected of causing mortality

in some plantations (Curtis and Foiles 1962). Because of the virulence of some diseases, the speed with which they act, and the investment made in establishment of regeneration, it is important to maintain efficient forest disease surveys.

Insects.--Young seedlings may be attacked aboveground by grasshoppers, cutworms, aphids, and bark-chewing beetles. One instance of heavy feeding by tussock moth in a ponderosa pine plantation has been recorded (Curtis and Foiles 1962). Root-feeding insects, such as grubs, weevils, wireworms, cutworms, root aphids, and root bark beetles, do their greatest damage to tree seedlings. Ponderosa pine seedlings are attacked by insects that reduce growth, deform, and occasionally kill trees. Insects causing this kind of damage include tip moths or twig moths, weevils, and midges and other gall-forming insects. Bark beetles, especially those of the genus *Ips*, can be very destructive to small, thin-barked pines. Insect populations and the damage caused by them vary greatly by years and locations. Efficient insect surveys will help to indicate potentially hazardous insect populations so they can be avoided or controlled if possible.

Climate.--Injury and mortality from climatic elements account for only a small percent of losses in established ponderosa pine regeneration. Extremes of climate or weather can be very destructive, however, especially in plantations grown from the wrong seed source. Snow and wind are also capable of causing understocking in sapling stands.

Mammals.--Mammals such as ground squirrels, pocket gophers, rabbits, hares, porcupines, and deer can cause malformation or mortality of stems of apparently established seedlings by their feeding. Defects often develop in the trees if they survive the attacks. The feeding of these animals is usually confined to small areas, and reflects either habitat conditions or sudden population increases. Nevertheless, understocking to a greater or less extent can result. Hares (Hall 1971), porcupines (Baker and others 1921; Wilson 1952), pocket gophers (Dingle 1956), and deer (Adams 1951a,b) are probably the most common and the most destructive.

The most common injury to established regeneration is from rodents. For control, the particular mammals causing damage must be identified. Keys are helpful in distinguishing these animals and the damage they inflict on the tree (Pearce 1938, 1947; Lawrence and others 1961).

Rabbits and hares are perhaps the easiest to control by the distribution of poisoned grain or alfalfa in suitable places, although the proper timing may not be evident until some feeding activity has been observed. Professional wildlife personnel can be helpful as advisors.

Various methods have been employed to reduce porcupine populations, but baiting with wooden blocks containing strychnine is the simplest and most effective (Hooven 1971). Trapping and poisoned baits have been used to control pocket gophers (Dingle 1956) and other rodents. Most poisons are potential hazards for other animals, and should be used under the supervision of the Fish and Wildlife Service.

Where deer populations become excessive, their browsing and trampling can be very destructive. In northwestern Montana, effects of deer browsing on planted and natural ponderosa pine seedlings were compared inside and outside of fenced deer enclosure plots (Adams 1951a,b). On the unfenced plots, over half of the planted pines were killed or heavily browsed the first year; more than 80 percent of the trees were dead after 4 years. Browsing also destroyed more than 80 percent of natural seedlings in a similar test. Regulating deer numbers by hunting, or increasing the amount of other browse available are possible methods of reducing deer damage. In plantations where intensive treatment is possible, the coating of leaders with chemical repellents has provided good protection from deer for 1 year in the Southwest (Heidmann 1963).

The damage to regeneration by sheep and cattle is due mostly to trampling. In an early study (Sparhawk 1918) mortality from grazing animals varied from 0.7 percent in the 3-1/2- to 4-1/2-foot high seedling class to 59.2 percent in seedlings less than a year old. Fortunately, damage from grazing stock can be avoided and their exclusion should be part of the management plan until the average tree is 4-1/2 feet high.

Competition.--No other mortality cause is as relentless as the contest among individuals for light, moisture, or nutrients. Moisture is scarce in the growing season on typical ponderosa pine sites, and therefore the more complete and the more enduring the reduction of competition, the greater the survival of seedlings. After the seedlings become established, competition develops between trees of the new stand. This can be controlled by management through regulation of the stocking density of the stand. Stocking density affects the growth of the trees as well as their survival, health, and vigor. Desirable stocking for different management goals is determined by complex biological and economic considerations. Accumulated evidence indicates a rather wide range of densities within which total stand volume growth is nearly constant. Thus, forest managers have considerable latitude in managing individual stands according to their needs.

Some degree of stocking control is needed in ponderosa pine stands of the northern Rockies, even though the actual stocking favored may vary. Control of the growing stock through management will reduce the volume of wood lost through competition in overstocked stands and advance the date when trees reach merchantable size.

Summary

This paper summarizes present information on natural and artificial regeneration of ponderosa pine in the territory served by the Intermountain Forest and Range Experiment Station. In this area, ponderosa pine grows under a wide range of conditions typified by varying rainfall, high temperatures, and low humidities during the growing season, mountainous topography, and great diversity of soil types and depths. It is a climax or seral species in 11 habitat types, ranging from warm and dry to cool and moist.

The ease with which ponderosa pine can be regenerated varies with conditions; therefore, no single regenerative technique can be employed with success everywhere. Some generalities, however, apply in varying degrees to ponderosa pine stands throughout the Intermountain Station territory.

Some kind of site preparation is necessary to establish either natural or artificial regeneration. Because soil moisture is a critical factor in seedling establishment, competition from other vegetation must be effectively reduced. Techniques include hand scalping, mulching, use of herbicides or fire, and machine stripping and terracing.

Planting has become an established method of regenerating brushfields and timber sale areas. Several planting systems are used successfully. Trees may be planted by hand or by machine on well-prepared sites. Seed source, for either direct seeding or planting, must be carefully chosen. Seed supply varies widely from year to year.

Direct seeding has never been used as extensively as planting in this region, although some seedings on favorable sites have been successful. The major factors in successful seeding are good site preparation, and protection from seed-eating rodents and birds.

In planting, healthy nursery stock and care in handling and field planting are essential.

Successful natural regeneration of ponderosa pine depends on a combination of abundant seed supply and minimum competing vegetation. Good cone crops occur irregularly so site preparation may have to be delayed to coincide with a heavy seed crop. In years of heavy seed crops, several high forest methods of reproduction cutting have been shown to produce sufficient seed for regeneration; seed-tree, shelterwood, group selection, and stem selection cutting have been tested. These methods are successful to varying degrees, depending partly on the habitat type of the stand location.

Numerous natural forces cause mortality of trees of different ages. Squirrels, chipmunks, and mice are responsible for the greatest losses in seed and can harvest most of the seed crop in light and medium years. The chief cause of seedling loss during the period of establishment and after germination or planting is drought, which often accounts for more than half of total mortality in the first 3 years. The losses can be reduced by rodent control measures, adequate site preparation, or thinning, weedings and thinnings. Other causes of mortality, such as fire, insects, diseases, and animals, are more sporadic. Control of these forces requires regular surveillance and prompt action when required.

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Present knowledge of natural and artificial regeneration of ponderosa pine in the northern Rocky Mountains and Intermountain West is summarized. Some regeneration techniques that have been tested in this territory are described. Planting is the most successful method of artificial regeneration; direct seeding is sometimes used. Several cutting methods may provide for natural regeneration if properly applied.

OXFORD: 23:231:232. KEYWORDS: regeneration, natural regeneration, artificial regeneration, reproduction cuttings, site preparation, ponderosa pine.

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U.S. FOREST SERVICE

MATCHACURVE-3: Multiple - Component and Multidimensional Mathematical Models for Natural Resource Studies

Chester E. Jensen



**INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Ogden, Utah 84401**

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THE AUTHOR

CHESTER E. JENSEN is Principal Statistician for the Intermountain Forest and Range Experiment Station. Previously, he held the same position at the Northeastern and Central States Forest Experiment Stations. Mr. Jensen, who holds a master of forestry degree from Michigan State University, received his training in graduate statistics at Iowa State University.

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Robert W. Horton, Director

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ABSTRACT

Mathematical model development procedures for graphed relations between variables are presented. As an extension of single-component two-dimensional model alternatives given in the two previous papers of the Matchacurve series, the author concentrates on multiple-component and multidimensional modeling. These procedures are particularly useful in describing unique main effects and interactions. A detailed application is given for a heavily convolute surface developed from "live" data.

INTRODUCTION

Phenomenal development of computer capability almost everywhere has spurred a surge in the use of mathematical models. Their use varies from the relatively simple statistical evaluation of model performance on new data sets to the automation of repeated model estimates as inputs to extensive compilation processes.

Of primary concern in this paper is the development of such models from a specific source, namely, *graphed relations* between continuous variables. The graphs may have been generated from theory, experience, graphic analysis of data, or from some combination of these. But, whatever the source, it is assumed that the graphs are *at hand* and that mathematical expressions for these relationships are required by the analyst.

We limit our task to finding transformations of the independent variables that, when scaled to the graphed relation, emulate the latter with a degree of accuracy satisfactory to the analyst.

Hoerl (1954) assembled a broad array of mathematical curve-form alternatives and presented numerous examples graphed to a relatively constant scale. Those conforming generally to the data trends (or curves from any other source) to be emulated could be fitted to the data (e.g., by least squares) or simply scaled to any graph. Performance could then be evaluated by the analyst and the best alternative adopted. Bartlett (1947) and Draper and Hunter (1969) recognized the necessity for allowing the analyst to make this judgment based on his own acceptance criteria. Isolated families of mathematical forms were discussed by Dolby (1963), Box and Tidwell (1962), and by Draper and Hunter (1969).

After considering these and other relevant publications on transformation, additional systemization of curve-selection processes seems in order. Moreover, it is felt that we should implement new efforts to bridge the communication gap between the practicing analyst and the more mathematically erudite transformation architect. Tukey and Wilk (1965) may have had such efforts in mind when they wrote: "As in the past, much, perhaps most, of even carefully collected data will not be completely analyzed. In part, this is because ... the technology of data analysis is still unsystematized and many of those who could put its tools to good use are unable to do so effectively."

Also, publications to date dwell heavily on the two-dimensional aspects of curve-form description; they place little emphasis on the details of specific approaches to the isolation and description of interactions in three or more dimensional relations. Such interactions are implicit in the majority of relations for the multitude of disciplines we encounter in Forest Service research.

Researchers have expressed a need for modeling techniques that are sensitive to unique main effects and interactions, techniques that can be applied by the analyst group in general. In response, we have elected to work with two fairly flexible families of mathematical forms (Jensen and Homeyer 1970, 1971). Curve-form selection from these sources has been systematized for two-dimensional relations. In addition, we have developed the descriptive capability of multiple-component mathematical forms, a method for the selection of an approach to descriptor development for three or more dimensional relations, and a method for the selection of an approach to descriptor development for three or more dimensional relations.

We are concerned primarily with the mathematical description of established graphic relationships. However, it seems advisable to begin by putting the whole modeling system (graphic-plus mathematical development) in analytical perspective, particularly where the graphed model is developed *from data*.

Here, guided by constraints known to exist in the relationship being modeled, unique main effects and interactions visible in the data can be drawn with interpretive freedom and few mathematical obstacles. Effects that cannot be identified in the data, are negligible in a practical sense, or are inconsistent with expectation, can be deleted. The graphic model thus derived can be described mathematically and fitted as a unit to original or new data sets by least squares. Finally, the fitted model can be evaluated statistically for performance.

At the graphing stage, shapes and scales for the effects of variables are not likely to be developed with mathematically rigorous attention to the fitting process. This is a potential source of bias and/or information loss. Ultimately, of course, a complex form-development problem is fraught with similar difficulties in any other modeling system. The solutions are generally heavily assumptive.

As visualized here, the screening of components in a graphic model is strongly subjective and probably insensitive to lesser effects, but it is still rational. The loss in screening power here, compared to that of rigorous testing systems, is counterbalanced by high sensitivity in the identification of complex curve forms admitted to the graphic screening process.

Given an accurate mathematical descriptor of the graphed model, the model can be fitted as a unit to a pertinent data set; i.e., a gross, least-squares adjustment for elevation and scale of the model in space. So, at least at one stage in model development here, objectivity is achieved in the fitting process.

In summary, the strength of this model-building system seems to lie in its sensitivity to complex forms and simplicity of curve-form development. Its weakness is lack of objectivity and lack of sensitivity to minor effects in any screening effort. However, for relations wherein strong interactions are expected, we judge the advantages to predominate.

But, for the majority of applications we have witnessed, prior information is so weak that it provides only general curve-form guidance; it offers little or no information on specific algebraic transformations of the independent variables likely to emulate response curves in the population involved. As a result, the analyst often submits an elementary array of rather arbitrarily selected components (e.g., X_1 , X_2 , X_1^2 , X_2^2 , X_1X_2) to the screening process. Here, the potential is great for curve-form bias and for unexploited information in the data, especially when there is a general expectation for curves and/or interactions in the relation. Speed and economy, but not necessarily sensitivity, characterize such an analysis.

The screening process above can be amended to include the development of progressively more sensitive components based on the analysis of residuals from sequentially fitted models. If so, it more nearly possesses the attributes of the graphic model-development approach; i.e., the components are selected to match data trends *visible* in the data.

By way of summation, there is substantial incentive for developing a model graphically when only general expectations exist for a relation (the usual case) and when those expectations include curvilinear main effects or interactions of any form (again, the usual case).

GRAPHIC MODELING

To begin with, let's consider graphic forms as they are necessary to our mathematical modeling strategy. For example, a graph for a two-dimensional (2-D) relation might appear as in figure 1.

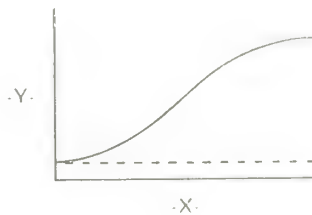


Figure 1

For 3-D relations, a graph might be presented as a complete surface (fig. 2).

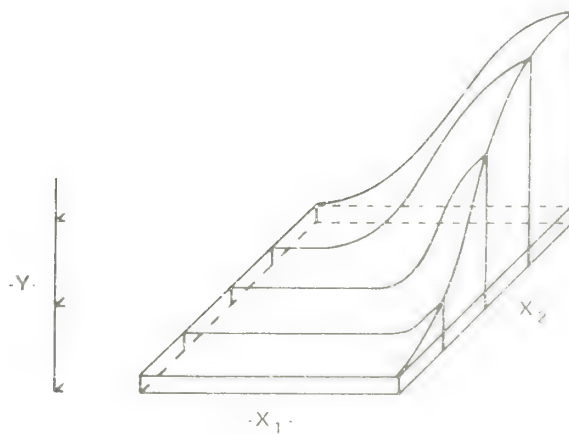


Figure 2

But, for purposes of model development here, it is only necessary to show 2-D graphs (e.g., Y over X_1) at representative points in the third dimension (fig. 3).

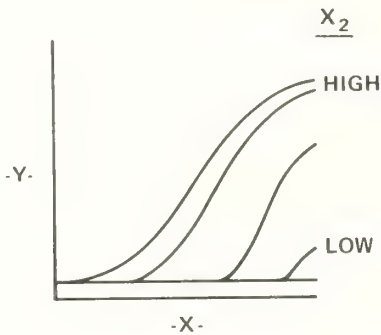


Figure 3

For 4-D relations, the 3-D sets of 2-D graphs can be shown at representative points in the fourth dimension (fig. 4),

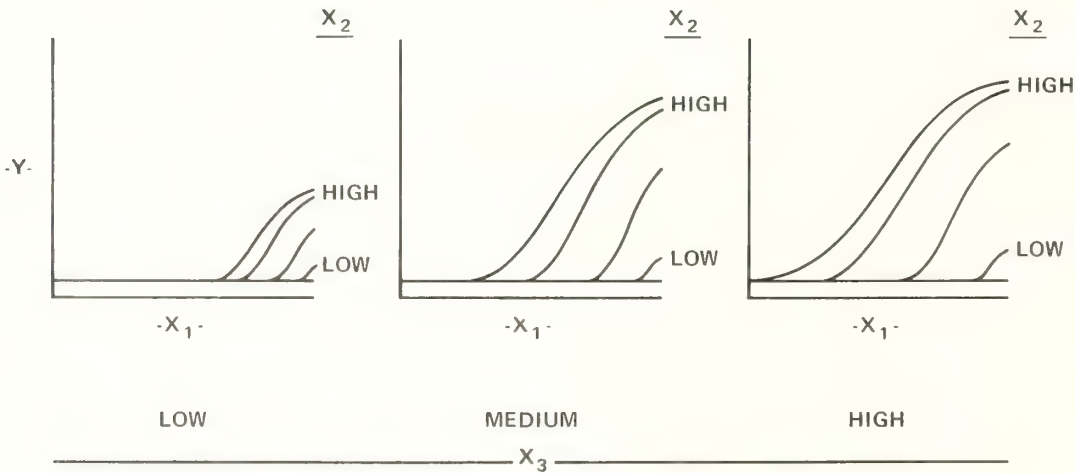


Figure 4

and so on for more dimensions.

MATHEMATICAL DESCRIPTORS

Two Dimensions

GENERAL

This system of graphic display might be described as *ultimately* 2-D, as are the mathematical models developed here. For example, in any *one* of the foregoing 3-D graphs, the specific 2-D sigmoidal shape of Y over X_1 would be identified from Matchacurve-1 (Jensen and Homeyer 1970) for each level of X_2 .

Changes in the shape-controlling parameters (P_i) of these sigmoids would then be expressed as 2-D functions of X_2 , as would the intercepts and scalars (the differences between maximum heights and intercepts) of these curves. The descriptor for the surface, composed of 2-D components, would be:

$$Y = \text{intercept} + \text{scalar} (\text{sigmoid})$$

where:

intercept = constant in the above examples, but *could*

$$= f_a(X_2)$$

$$\text{scalar} = f_b(X_2)$$

$$\text{sigmoids} = f(P_i), \text{ and}$$

$$P_i = f_i(X_2)$$

The same procedures can be extended to four or more dimensions. Then, *the capability for developing accurate descriptors for graphed relations in three or more dimensions depends largely on his ability to find or create accurate 2-D descriptors.*

MULTIPLE-COMPONENT DESCRIPTORS

In Matchacurves-1 and -2, Jensen and Homeyer (1970, 1971) provide 2-D descriptors for a fairly broad array of curve forms.^{1/} When a suitable "match" for a graphed curve cannot be found, 2-D descriptors can generally be developed by sequentially "matching" segments of the graphed curve and adding descriptors for the parts to arrive at the whole.

^{1/}The reader should be familiar with the content of both publications to ease assimilation of the procedures herein.

Introductory Example

A commonly encountered kind of curve form that departs from the single-component Standards of Matchacurves-1 and -2 is represented by the graphed curve in figure 5.

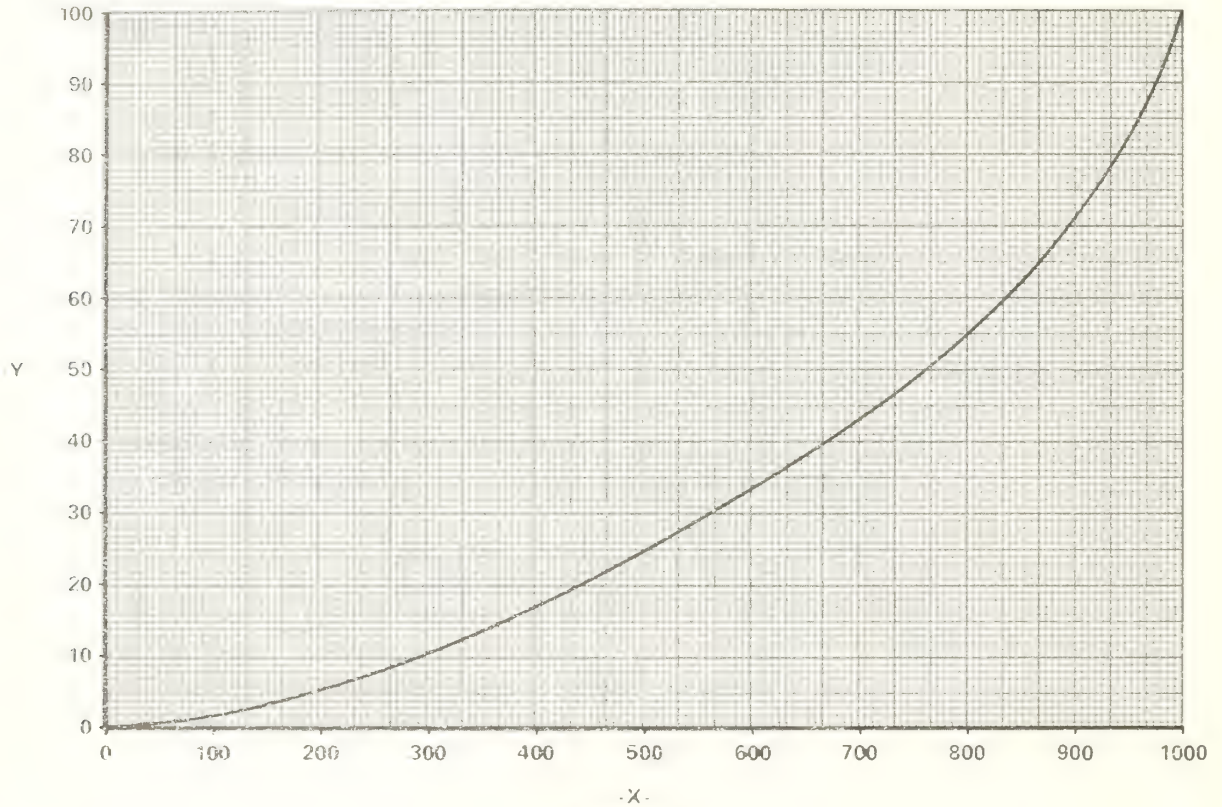


Figure 5

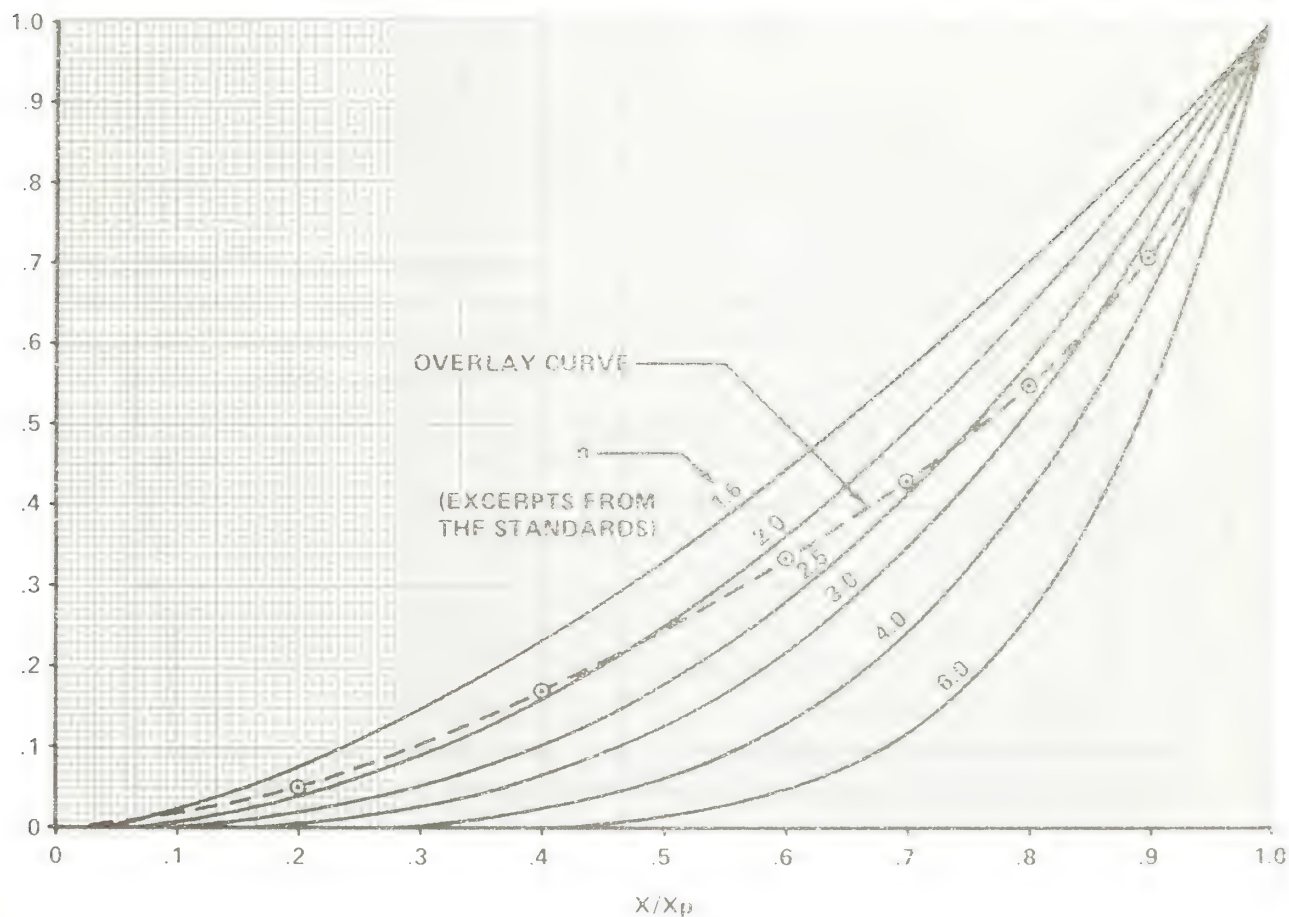
Assume this is the curve to be described. Now, a discerning analyst will immediately *reject* it as a single-component exponential form because of the second pronounced bend in the curve at $700 \leq X \leq 1000$. But, let us run it through Matchacurve-2 procedures to provide a contrast for a two-component form to be developed subsequently.

Representative points of the curve are scaled to a maximum of 1.0 in both X and Y below,

Table 1

X	(X/1000)	Y	(Y/100)
0	0.0	0.0	0.00
200	.2	5.2	.05
400	.4	17.0	.17
600	.6	33.5	.34
700	.7	43.0	.43
800	.8	54.8	.55
900	.9	71.1	.71
1000	1.0	100.0	1.00

and are replotted as a 5- by 7.5-inch, 0.125-inch grid. The overlay curve, the same size as the Standards (fig. 6):



A-1. — Standards for position A, set 1 — (X-transform to be fitted by least squares = $(X)^n$, $0 \leq X \leq X_p$)

Figure 6

As is evident, there is no suitable match for the overlay curves in the $n > 1.0$ Standards (set A-1). Although overlay curves are not shown, the same holds true in the $0 < n < 1.0$ (set A-2) and the $n < 0$ Standards (set A-3).

Having thus exhausted the *single-component* Matchacurve-2 alternatives, we now resort to description of the graphed curve in two pieces. The first part selected covers the range $0 \leq X \leq 700$ since that portion of the curve in figure 5 has only one

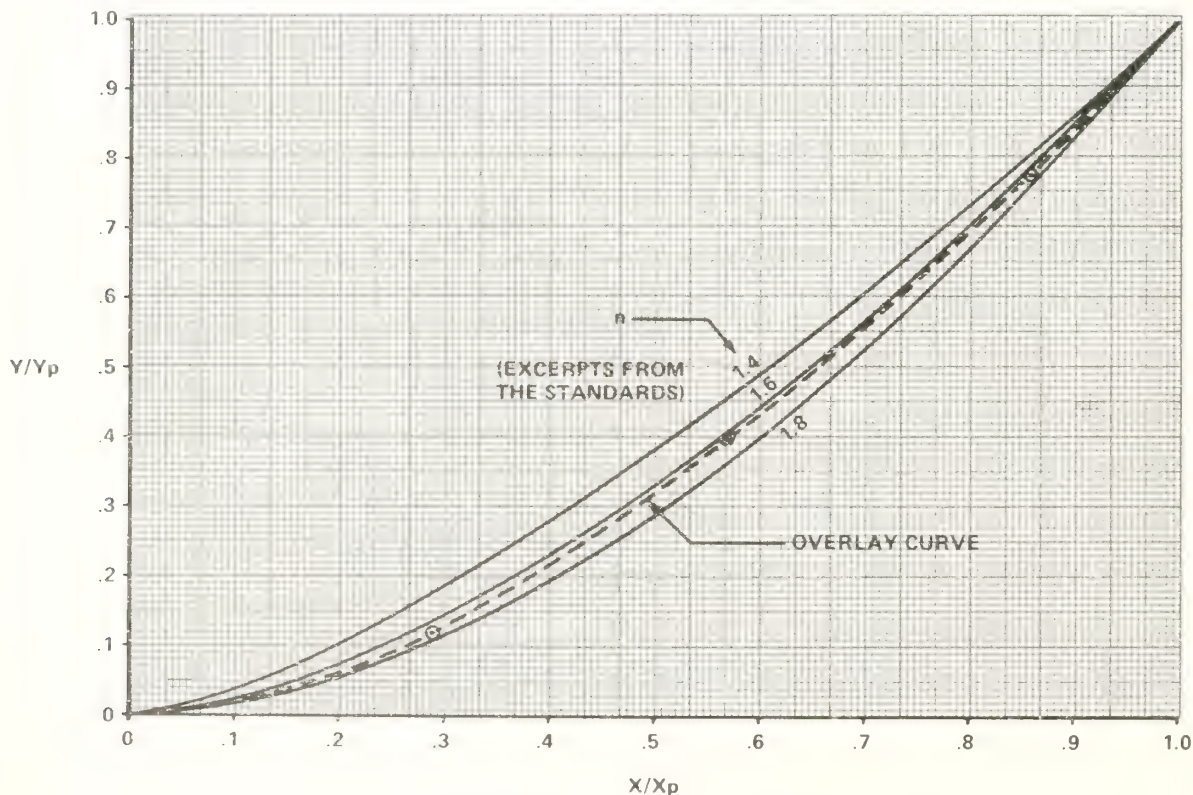
point of bend and seems reasonably similar to the conformation of the $n > 1.0$ Standards. Next, X and Y are scaled to 1.0 at $X = 700$ (table 2, columns 1-4).

Table 2

X	$(X/700)$	Y	$(Y/43.0)$	$bX^{1.65^{1/}}$	$Y-bX^{1.65}$
0	0.00	0.0	0.00	0.0	0.0
200	.29	5.2	.12	5.4	-.2
400	.57	17.0	.40	17.1	-.1
600	.86	33.5	.78	33.3	.2
700	1.00	43.0	1.00	43.0	.0
800		54.8		53.6	1.2
900		71.1		65.1	6.0
1000		100.0		77.5	22.5

$$1/b = 43.0/(700)^{1.65} = 0.0008691$$

After plotting an overlay curve and comparing it to the $n > 1.0$ Standards (fig. 7),



A-1. — Standards for position A, set 1 — (X -transform to be fitted by least squares = $(X)^n$, $0 \leq X \leq X_p$)

Figure 7

we find that $X^{1.65}$ gives a good match for the curve in the range $0 \leq X \leq 700$. $X^{1.65}$, scaled to 43 at $X = 700$, gives a fairly close approximation of the representative Y values (table 2, column 5). As might be expected, this relatively flat curve is too flat when extended to represent the desired curve in the $700 < X < 1000$ range. The differences, 1.2, 6.0, and 22.5 (table 2, last column), represent the curve of values that must still be added to match the desired curve. Needed in the descriptor is a second component that is zero in the $0 \leq X \leq 700$ range and about equal to the curve of values just indicated in the range $700 \leq X \leq 1000$.

By scaling X and $(Y-bX^{1.65})$ to 1.0 at $X = 1000$ (table 3, columns 1-4),

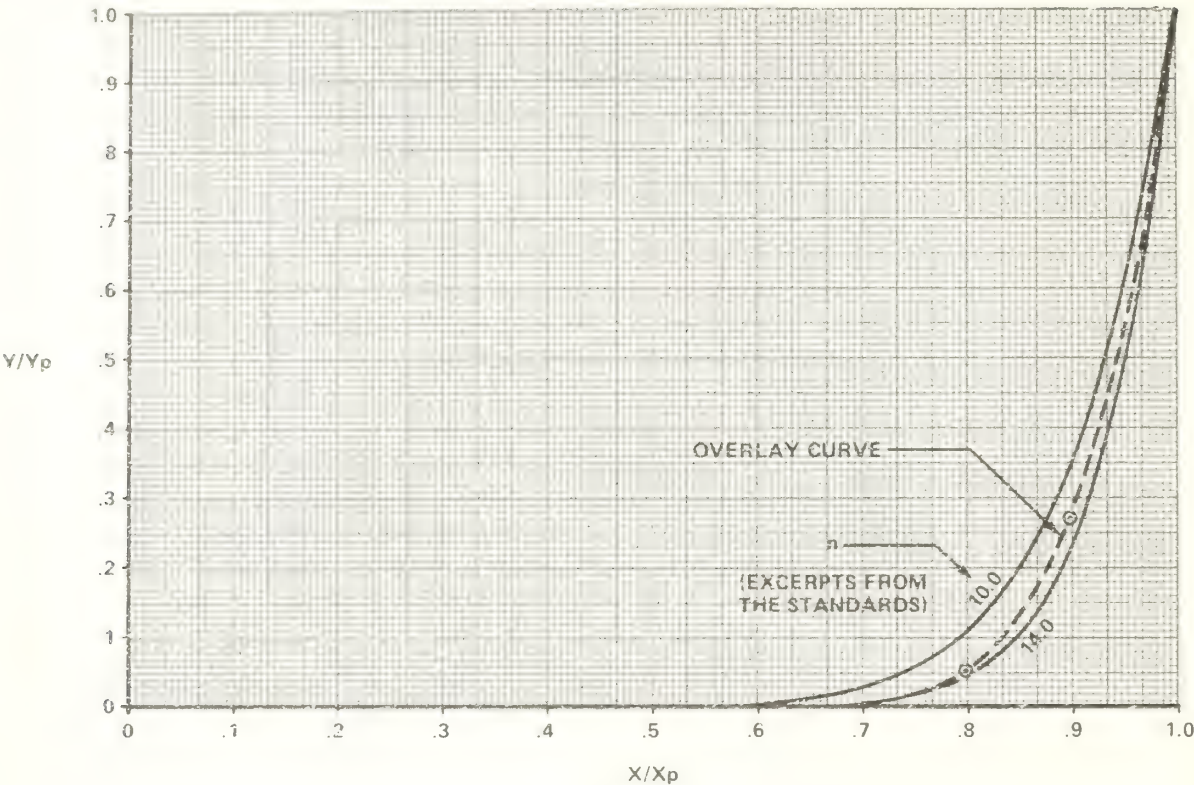
Table 3

		$(Y-bX^{1.65})$		
X	(X/1000)	Y	$(Y-bX^{1.65})$	$(Y-bX^{1.65})/22.5$
0	0.0	0.0	0.00	0.0
700	.7	.0	.00	.3
800	.8	1.2	.05	1.4
900	.9	6.0	.27	6.0
1000	1.0	22.5	1.00	22.5

$$b = 22.5/(1000)^{12.5} = 7.115 \cdot 10^{-37}$$

^{2/} The generating of curves that lie between the Standards of either Matchacur or -2, along with the compounding and verification of more complex forms, virtually necessitates ready access to a computer. A small, desk-top computer is ideal for the tasks at hand. It should have at least: 250 words of program storage, 10 store registers, capability for X^n , e, conventional mathematical operations, and recorded input and output potential.

making an overlay curve, and comparing it to the $n > 1.0$ Standards (fig. 8),



A-1. - Standards for position A, set 1 - (X -transform to be fitted by least squares = $(X)^n$, $0 \leq X \leq X_p$)

Figure 8

we find that X^{13} might match the required curve fairly well, but, on trial, $X^{12.5}$ performs a little better. Scaling $X^{12.5}$ to 22.5 at $X = 1000$ gives values close to those desired in the $700 \leq X \leq 1000$ range (table 3, column 5). Then the complete descriptor is:

$$\hat{Y} = (8.691 \times 10^{-4}) X^{1.65} + (7.115 \times 10^{-37}) X^{12.5}$$

with final values listed in table 4. In this case, $\hat{Y}$ is regarded as being satisfactorily close to Y .

Table 4

X	Y	$\hat{Y}$
0	0.0	0.0
200	5.2	5.4
400	17.0	17.1
600	33.5	33.4
700	43.0	43.3
800	54.8	55.0
900	71.1	71.1
1000	100.0	100.0

The computational ideas just shown are applicable to other curve forms, but a larger array of ideas may be necessary to independent descriptor efforts by the reader. The examples that follow are presented with decreasing explanatory detail as seems appropriate to the stage of discussion. We will start with an abbreviated version of descriptor procedures for the above example (fig. 5).

Section A, Multiple Exponentials Without Inflection

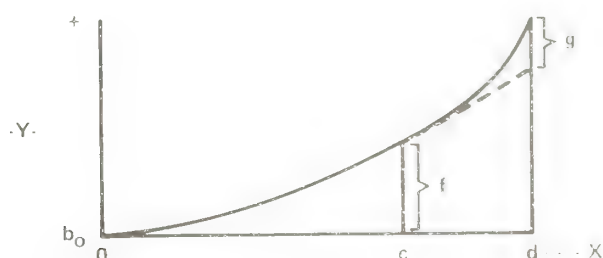


Figure 9

- 1.--Read a set of representative XY points from the graphed curve (fig. 9). Select one X-value in this set, point c, such that the curve over the range 0 to c appears to have about the same general conformation (one point of bend) as the Standards of Matchacurve-1 (sets A-1, A-2, or A-3 for this spacial orientation).
- 2.--"Match" this exponential curve in the range 0 to c and determine n in X^n .
- 3.--Scale X^n to f at c, $b_1 = f/c^n$. Then, $\hat{Y}_1 = b_0 + b_1 X^n$.
Extend $\hat{Y}_1$ over the range c to d (dotted line).
- 4.--Match the exponential curve of residuals over the range 0 to d and determine m in X^m .
- 5.--Scale X^m to g at d, $b_2 = g/d^m$. Then, $Y_2 = b_2 X^m$.
- 6.--Add components Y_1 and Y_2 . Then,

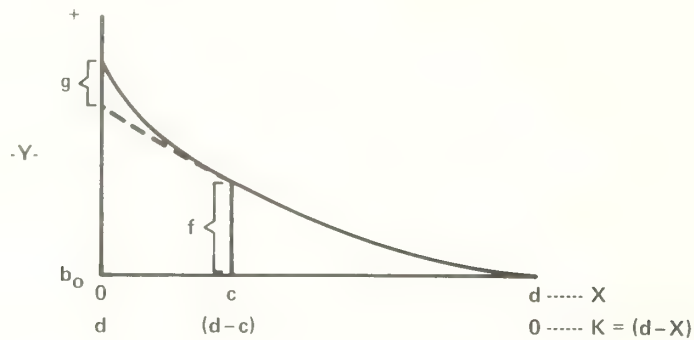
$$Y = b_0 + b_1 X^n + b_2 X^m, \quad b_0 = 0.$$

If the intercept is some value other than zero, the above procedures apply to the differences between the intercept and the graphed curve. And, as before,

$$Y = b_0 + b_1 X^n + b_2 X^m, \quad \text{but } b_0 \neq 0$$

Alternative orientations of the above curve in space can be handled simply, as follows:

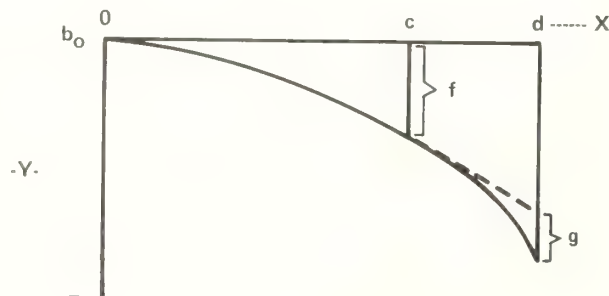
Figure 10



In this case (fig. 10), the original curve is reversed in X. Substitute $K = (d-X)$ for X and follow the foregoing steps 1-6. Then,

$$\dot{Y} = b_0 + b_1 K^n + b_2 K^m, \quad 0 \leq X \leq d$$

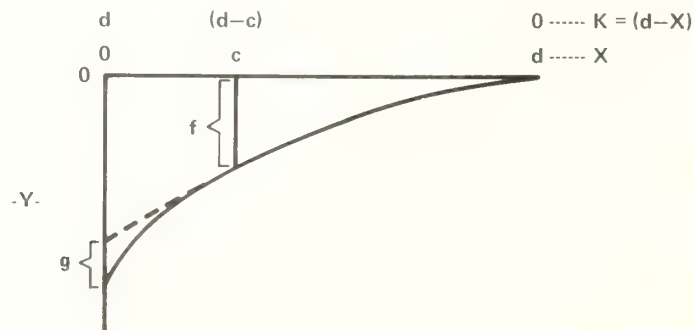
Figure 11



In Figure 11, the original curve is inverted about the intercept b_0 . Work with absolute differences between b_0 and the curve, for the first component. For the second component, work with absolute differences between the first component curve and the original curve. Follow steps 1-6, but subtract the two components from b_0 . Then,

$$\dot{Y} = b_0 - b_1 X^n - b_2 X^m$$

Figure 12



In figure 12, the original curve is first reoriented so that it is horizontal. Substitute k for X and work with absolute values. Then, subtract the two components from b_0 . Then

$$Y = b_0 - b_1 e^{-kX} - b_2 e^{-kX}$$

These mechanics for reorienting a curve have general application and greatly facilitate descriptor-development efforts.

Section B, Multiple Exponentials With Inflection



Figure 13 is a variant of the original curve in Section A. Steps 1-6 still apply, except that the last component is *subtracted* from the first. Then,

$$Y = b_0 + b_1 X^{11} - b_2 X^{11}$$

Alternative orientations of this curve in space can be handled as described under Section A along with appropriate changes in sign for the last component.

Section C, Multiple Exponentials With Flat Central Segment

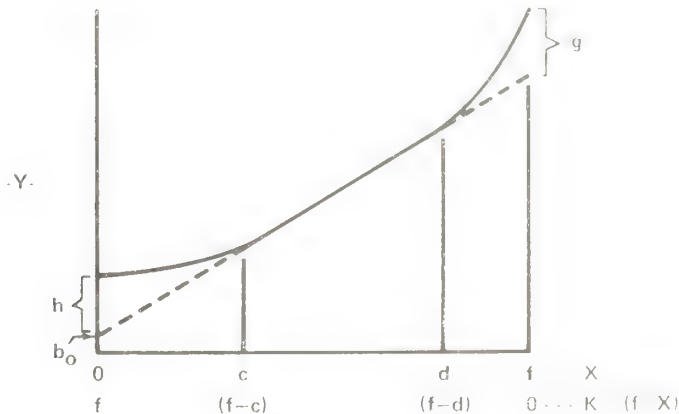


Figure 13

The descriptor for a curve that has an extended flat midsection (fig. 14) can often be treated as follows:

- 1.--Determine the intercept, b_0 , by graphic extension of the flat segment. Calculate the slope of the line. Then,

$$\hat{Y}_1 = b_0 + b_1X$$

- 2.--Determine the residuals of the curve from the straight line for representative points over X . Be sure to include three or four such points at each end of X , where the curve bends away from the straight line.

- 3.--For the right-end departures, symbolized here as Y_2 : scale X and Y_2 to 1.0 over the whole X -range; find a suitable n in X^n by using the Standards of Matchacurve-2; scale X^n to g at f , $b_2 = g/f^n$. Then, the right-end descriptor is:

$$\hat{Y}_2 = b_2X^n$$

- 4.--For the left-end departures, symbolized here as Y_3 : reverse the X -axis by substituting $K = (f-X)$; scale K and Y_3 to 1.0 over the whole range of X ; find a suitable m in K^m by using the Standards; and scale K^m to h at f , $b_3 = h/f^m$. Then, the left-end descriptor is:

$$\hat{Y}_3 = b_3K^m$$

- 5.--Then the entire descriptor is:

$$\hat{Y} = b_0 + b_1X + b_2X^n + b_3K^m, \quad 0 \leq X \leq f$$

Variants from this curve include negative departures from either or both ends of the straight line. In such cases, the signs of the corresponding components simply become negative.

Of course, there is no limit to the number of components that can be used in a descriptor, unless the analyst has algebraic simplicity rather than accuracy as an overriding objective. With electronic computer service available almost everywhere, computational complexity should not be a limiting factor.

Section D, Single Sigmoids

For any curve that has an inflection and a distinctive peak (positive or negative), the sigmoids of Matchacurve-1 generally offer more sensitivity than the exponentials. (Note that sigmoids may be created with two exponentials of opposite sign, as is partially detailed in Section B.). Sigmoids are shown here in combination with linear effects for added descriptive power.

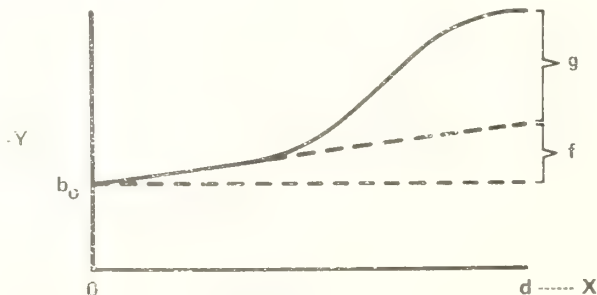


Figure 15

In this case (fig. 15), we can use a straight line with slope b_1 . The intercept plus the straight line is $Y_1 = b_0 + b_1X$. Then add the sigmoid matching the curve differences, Y_d , from the linear function, scaled to g at the point in X (d here) where Y_d peaks. The sigmoid matching process is analogous to steps 1-5 in Section A. Representative sets of X - and corresponding Y_d -values are scaled to 1.0. An overlay curve is made and compared to the sigmoid Standards of Matchacurve-1, and n and I for a matching curve are noted.

The final sigmoid component is $Y_2 = gE$, where:

g is the scalar for E

E , specified as Y/Y_p in Matchacurve-1 (page 4), symbolizes the e-transform, which varies from zero to one in the range $XP \pm XP$.

XP is the point in X where the sigmoid peaks in either a positive or a negative vertical direction.

n and I are appropriate curve-shape parameters identified from the matching curve in the Standards. These, along with XP , are necessary inputs to 1.

The final descriptor is then:

$$Y = b_0 + b_1X + gE$$

Alternative arrangements of the sigmoid about the straight line would require treatment as detailed under Section A, but a brief explanation follows:

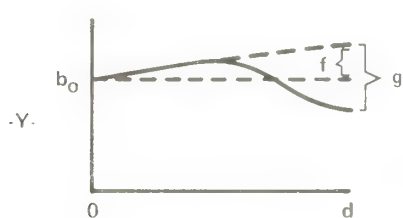


Figure 16

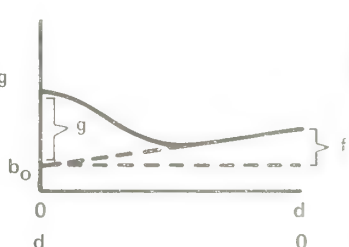


Figure 17

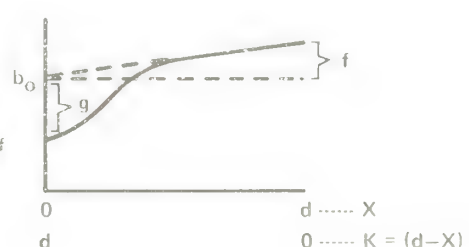


Figure 18

For figure 16

$X_p = d$ in the X -scale and the sign of the sigmoid component would become negative:

$$Y = b_0 + b_1X - gE$$

For figure 17

$K = (d-X)$ would be substituted for X in 1, $X_p = d$ in the X -scale, and the sigmoid would be positive:

$$Y = b_0 + b_1X + gE, \quad 0 \leq X \leq d.$$

³/Appropriate sigmoids can be selected from the Standards of Matchacurve-1.

For figure 18

Again, $K = (d-X)$ is substituted for X in E , $X_p = d$ in the K -scale, and the sigmoid is subtracted:

$$\hat{Y} = b_0 + b_1X - gE, \quad 0 \leq X \leq d.$$

The same sigmoid alternatives exist when the slope of the straight line is negative the only change in the descriptors would be that the sign of the first component would be negative.

Section E, Multiple Sigmoids

Sometimes the combination of several sigmoidal (upright or inverted) components can be used effectively to describe asymmetrical curves. Each sigmoid is matched and scaled independently and both are summed in the final descriptor.

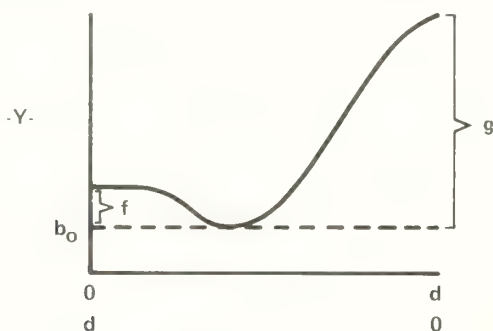


Figure 19

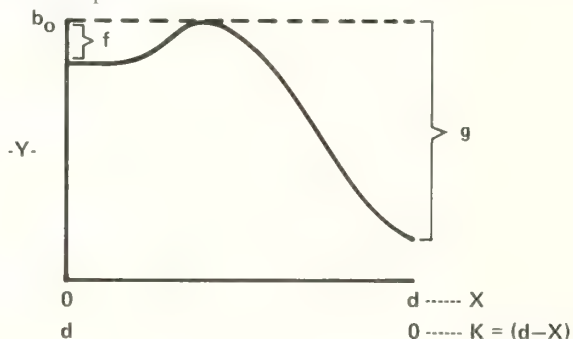


Figure 20

For figure 19

$K = (d-X)$ is substituted for X in E_1 , $X_{p1} = d$ in K , and $X_{p2} = d$ in X :

$$Y = b_0 + fE_1 + gE_2, \quad 0 \leq X \leq d$$

For figure 20

$K = (d-X)$ is substituted for X in E_1 , $X_{p1} = d$ in K , and $X_{p2} = d$ in X :

$$\hat{Y} = b_0 - fE_1 - gE_2, \quad 0 \leq X \leq d$$

Section F, Exponentials and Sigmoids

Of course, exponentials and sigmoids can be used in combination (fig. 21).

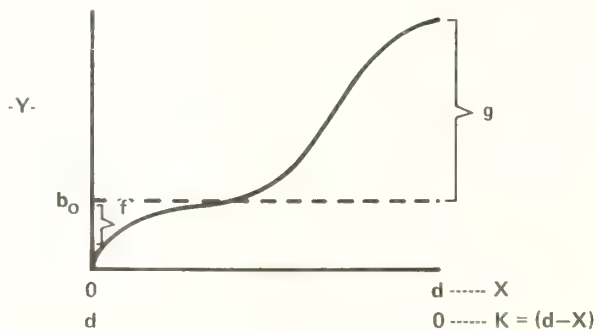


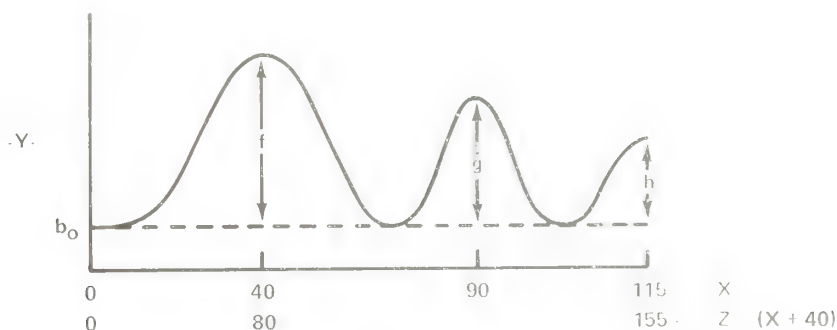
Figure 21

Where:

$$X_p = d \text{ in } X \text{ for } f, \text{ and } X = (X_p + X_p) = (X_p \pm X_p), \quad 0 \leq X \leq 115$$

Section C, Bell-shaped Curve

Bell-shaped curves, in whole or in part, can be described in $E = fE_1, gE_2, \text{ and } hE_3$. And, in this particular example (fig. 22),



the peaks of the two leftmost bell-shaped curves occur at points other than the extreme of the X-range, which is not true in previous examples involving sigmoids. A peculiarity of E is that its controlled use is within $XP \pm XP$, where XP is the point in the X-range at which the Y-peak (either positive or negative) occurs and $XP \pm XP$ are the points at which the tails of the bell-shaped curve drop to zero. Beyond these points, the sigmoid values become negative. Then, where an XP is used such that $XP \pm XP$ does not cover the pertinent range of X, it becomes necessary to alter the X-scale so that it does. The discussion below for the foregoing graph (fig. 22) should clarify both the problem and its solution.

"E" specifies a symmetrical, bell-shaped curve with values ranging from 1.0 at XP to zero at $XP \pm XP$. With $XP = 40$ for the first bell-shaped curve, the range of application for E is 40 ± 40 , or from zero to 80. Beyond $X = 80$, E would actually dip below zero by some unspecified amount. The problem is simply remedied by adding a large enough constant to X such that $XP \pm XP$ would cover the original maximum of 115. $Z = (X + 40)$ accomplishes this nicely; so the descriptor would be:

For the first curve,

$$Y_1 = fE_1, \text{ where } Z \text{ replaces } X \text{ in } E \text{ and } X_p = 80 \text{ in } Z;$$

for the second curve,

$$Y_2 = gE_2, \text{ where } X \text{ is used without transformation in } E, \text{ since } X_p = 90 \text{ gives an applicable range for } X \text{ of zero to } 180, \text{ covering the } X\text{-extreme of } 115 \text{ as required;}$$

for the third curve, the left half of a bell-shaped curve,

$$Y_3 = hE_3, \text{ where } X \text{ is also used without transformation in } E \text{ since } X_p \pm X_p (115 \pm 115) \text{ covers the pertinent range of } X, 0\text{-}115.$$

Then, the entire descriptor is:

$$\hat{Y} = b_0 + fE_1 + fE_1 + gE_2 + hE_3, \quad 0 \leq X \leq 115$$

where:

E_1 involves Z

E_2 involves X

E_3 involves X

Section H, Matching Parts of Exponentials or Sigmoids

On occasion, the added effort required to compile a multiple-component descriptor can be avoided by utilizing a *portion* of a single-component curve.

Assume the curve in figure 23 (A) below

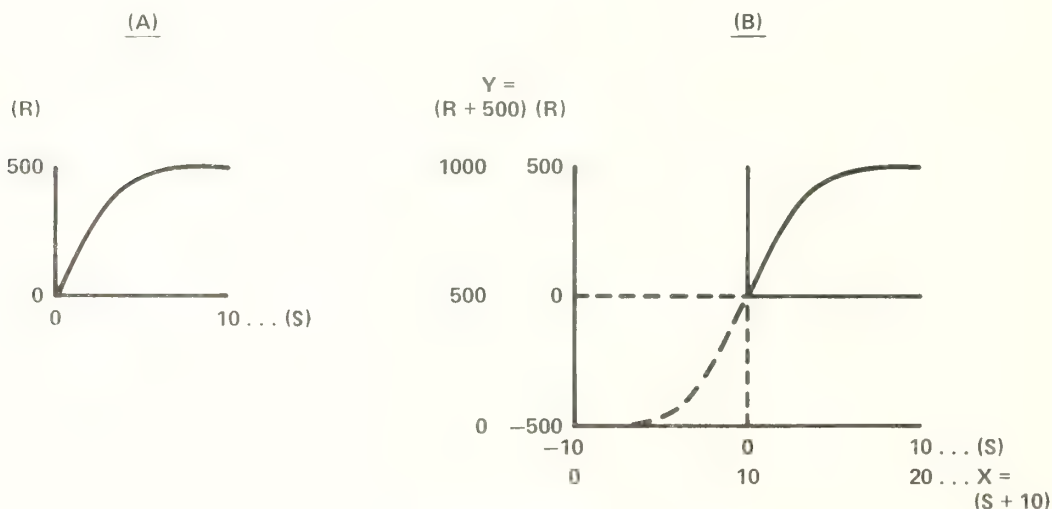


Figure 23

is to be described mathematically and that no satisfactory matching curve has been found in Matchacurves-1 or -2. As an alternative, the analyst *could* undertake a multiple-component description, but another single-component possibility exists. Extend the desired curve in (a) such that the resulting form approximates that of any sigmoid shown in the Standards. Add a constant to the abscissa such that $XP \pm XP$ covers the pertinent range of X . $(S + 10)$ turns the trick here. Also, add a suitable constant, 500 in this case, to R for overlay scaling purposes only. For representative points from the right half of this curve, scale the X - Y pairs to a maximum of 1.0, construct an overlay curve, and find a matching Standard for the upper half of the overlay. The adopted single-component standard fitted to the X - and Y -values then represents the original curve in the region $10 \leq X \leq 20$. The resulting descriptor is:

$$R = -500 + 1000 E$$

where:

$$X = (S + 10) \text{ in } E, \quad XP = 20, \text{ and } 0 \leq S \leq 10.$$

Procedures for any fraction of any form are analogous.

Summary Statement

In concluding the discussion for 2-D multiple-component descriptors, we reiterate that the analyst's capability for developing sensitive multidimensional models depends largely on his 2-D talents. The examples shown here, if understood, give enough procedural background to permit intuitive extension of the system to include more flexible curve-form alternatives. The "live" example, which will be presented later, merely serves to reinforce a few of these ideas through actual application.

Three Dimensions

GENERAL

Given 2-D curves over X_1 for representative levels of X_2 (fig. 24)

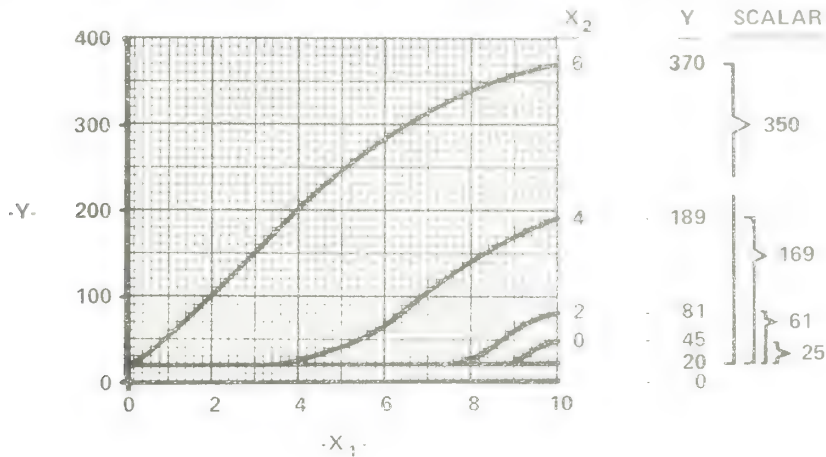


Figure 24

and given a 2-D descriptor,

$$\hat{Y} = \text{intercept} + \text{scalar} (X_1\text{-transform})$$

... for each such curve, the analyst is in a position to formulate a descriptor for the implied surface. He simply expresses the changing intercepts, scalars, and parameter(s) of the X_1 -transform in terms of X_2 . He then substitutes appropriately in the original 2-D descriptor.

Assume pertinent information for the four sigmoid curves above has been assembled by using Matchacurve-1 Standards (table 5, columns 1-6).

Table 5

Sigmoid parameters							
X_2	intercept	XP	n	I^*	scalar	scalar	I
0	20	10	3.0	0.90	25	25.0	0.900
2	20	10	3.0	.87	61	61.1	.870
4	20	10	3.0	.66	169	169.4	.665
6	20	10	3.0	.10	350	350.0	.100

*Let I = sigmoid inflection point in X_1 as a proportion of the range in X_1 .

Here, the intercept and the sigmoid parameters, XP and n, are constant over X_2 ; the scalar *increases* and I *decreases* exponentially with increasing X_2 -values. Using Matchacurve-2,

$$\text{scalar} = 25 + 9.028(X_2)^2$$

$$\hat{I} = 0.9 - 0.003704(X_2)^3$$

By substituting in the original equation for $\hat{Y}$,

$$\hat{Y} = \text{intercept} + \text{scalar} (X_1\text{-transform})$$

$$\hat{Y} = 20 + (25 + 9.028(X_2)^2) (\text{sigmoid})$$

where:

$$\text{sigmoid} = \frac{e^{-\left| \frac{(X_1/10)-1}{1-I} \right|^3} - e^{-\left(\frac{1}{(1-I)} \right)^3}}{1 - e^{-\left(\frac{1}{(1-I)} \right)^3}}$$

and I is as specified above.

By plotting computer solutions for $\hat{Y}$ at pertinent combinations of X_1 and X_2 , we can see that the descriptor lies quite close to the original curves (fig. 25).

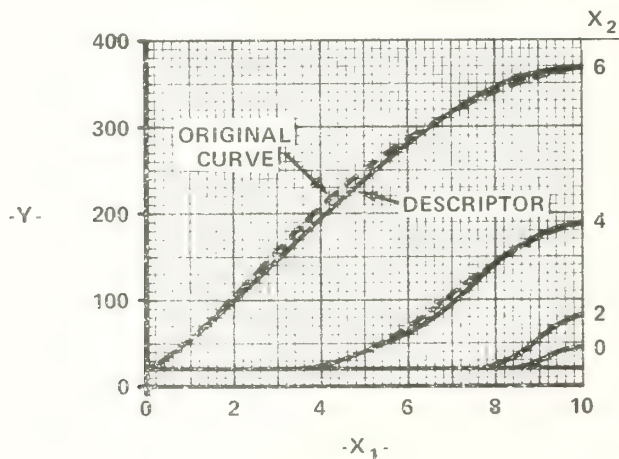


Figure 25

Then, the entire predicted surface appears as follows (fig. 26):

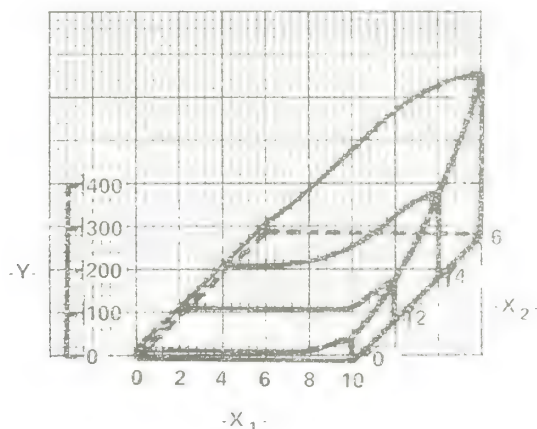


Figure 26

Note that the original curves may be given over X_2 instead of X_1 , in which case, the roles of X_1 and X_2 in descriptor development would be interchanged. Also, where multiple-component 2-D descriptors are necessary for the original curves, each component can be treated as a separate X-transform to be added in the final descriptor.

This descriptor system is applicable to virtually any surface and is especially useful in emulating strong interactive relationships. An application to a "live" data set^{4/} involving such interaction is documented below as a means of demonstrating actual use of some 2-D alternatives available to the analyst.

"LIVE" DATA EXAMPLE

On each of 16 passes over a level target area, 600 gal of fire retardant were dropped from an aircraft. Square-foot coverage and volume of material reaching the ground per 100 ft² were measured for each drop along with drop height, windspeed and direction, aircraft speed, temperature, humidity, and so forth. Interest centered on the change in coverage of ≥ 2 gal/100 ft² over a controlled range of drop heights within a partially controlled range of windspeeds.^{5/}

Suppose the plane were rolling along the ground (drop height = 3 ft) at normal flying speed and in the absence of wind, it would be expected that a 600-gal drop would be distributed over a relatively narrow strip of ground and that the area covered by ≥ 2 gal/100 ft² would be held to some nominal value. Increased aircraft (and drop) height should result in greater dispersal; maximum coverage should be reached at some optimal height. As drop height is increased beyond the optimum, dispersal of the retardant from air friction and evaporation should become more complete; coverage should finally reach zero at some relatively great drop height.

So expectation at zero wind is for a bell-shaped curve truncated to the left of the peak. With increasing wind, optimal drop height and peak coverage should decrease.

^{4/}The author is indebted to the Northern Forest Fire Laboratory, Fire Control Technology Project, Missoula, Mont., for the "live" data used here (George and Blakely 1973).

^{5/}The effects of all other variables were either negligible or unidentifiable in this data set.

since dispersal of the retardant would be accentuated by the horizontal shearing force of the wind. Thus, the expected surface was as shown in figure 27 below.

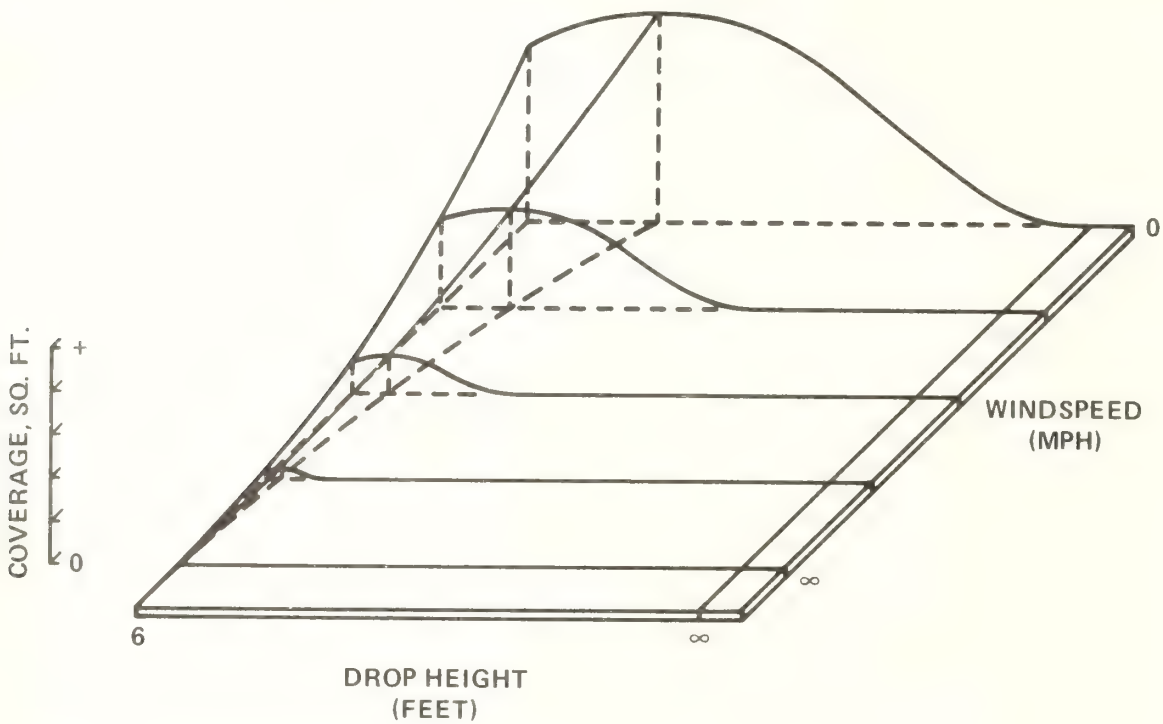


Figure 27

Using these expectations as guides, coverage, C, was curved over height, H, fitting the curves to actual data points by approximate least deviations (Karst 1958) for each of three data groups in wind, W (fig. 28):

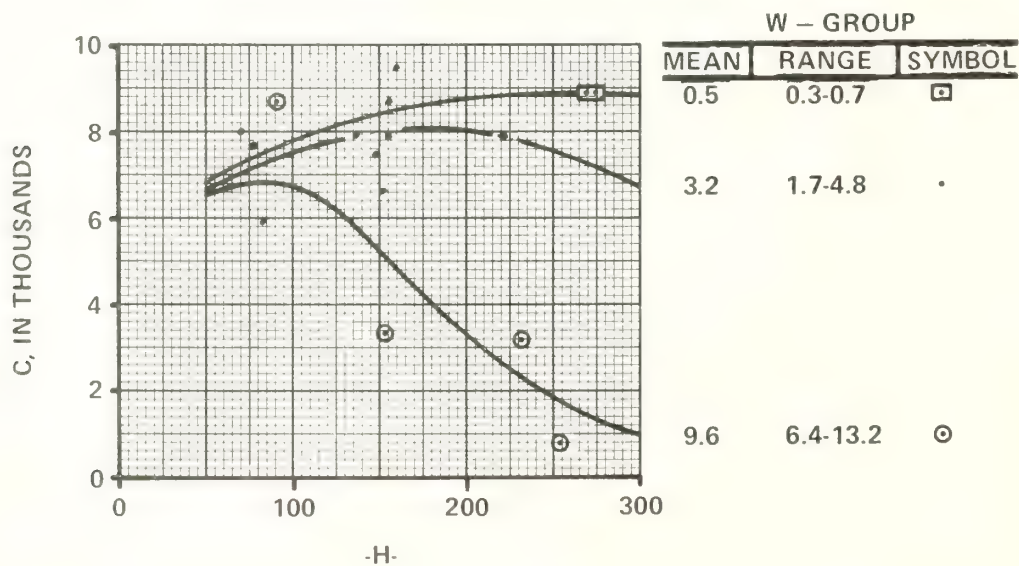


Figure 28

These curves, plotted at their respective W means, were connected over W to form the implied surface, figure 29. And, it can be seen that major features of the expectation are reflected in the data--*even within the limited range of H and W .*

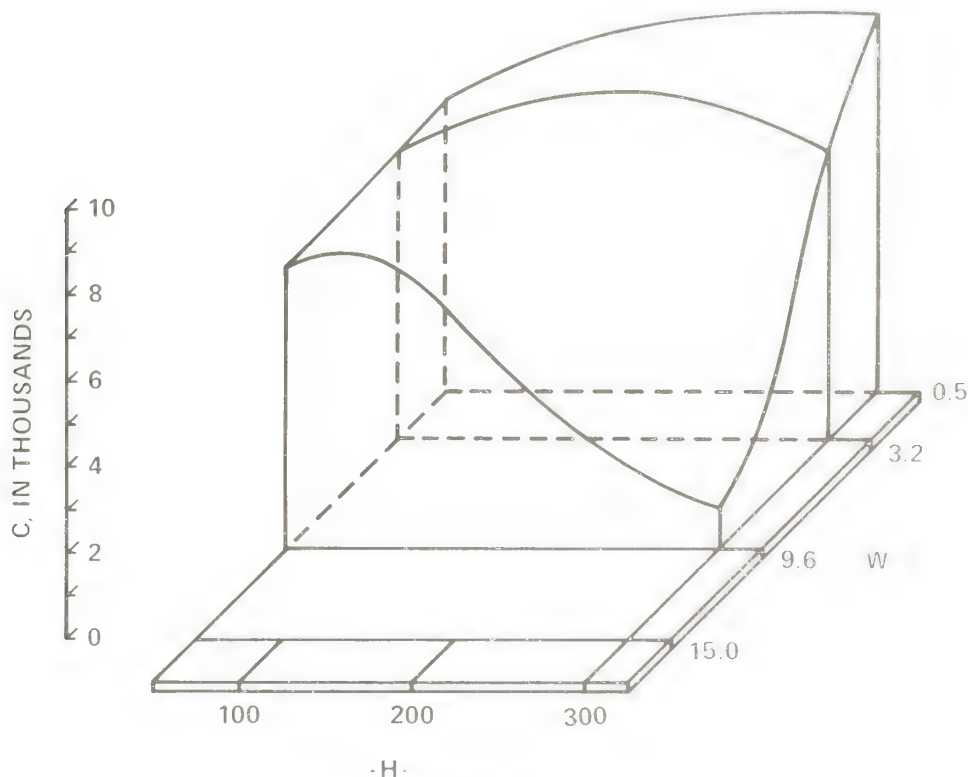


Figure 29

Figure 29, then, is the basic surface for which a descriptor was developed. Assuming that the curves over H (figs. 27, 28) could be suitably represented by segments of symmetric bell-shaped forms, the e-transform of Matchacurve-1 was deemed applicable and the problem of identifying matching e-transforms approached.

The e-transform is limited in that it will yield values of from zero to one in the full bell-shaped form only *within* the range $H_P \pm H_P$, where H_P is the point in H at which the C -values peak. And, it was a unique feature of this example that the maximum H -values for all three curves of the set exceeded $2H_P$ (fig. 30).

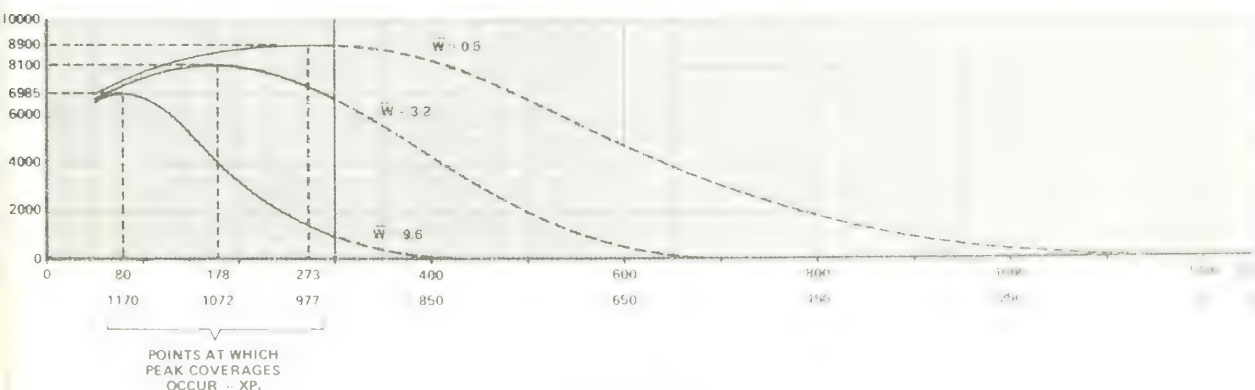


Figure 30

The broadest curve (for $W = 0.5$) was estimated to peak at $H = 273$. In this case, the e-transform would have dropped below zero where H exceeded $2HP$, or $2(273) = 546$, long before the approximate graphed limit of $H = 1150$ was reached.

One solution would have been to supplant H with a transform such as $X = (H + 1000)$. Then, since $2XP$ for the broadest curve would have been $2(273 + 1000) = 2546$ --safely beyond the upper limit of $X = (1150 + 1000) = 2150$ --the excess would allow for the slightly larger curve span likely to exist at $W = 0$.

The transform actually adopted, $X = (1250 - H)$, differed from $X = (H + 1000)$; the H -scale was reversed for a rather minor computational convenience and a slightly larger constant (1250) was selected, but the rationale was the same. Descriptor development is presented in terms of $X = (1250 - H)$.

Next, necessary inputs to the final coverage estimator were considered:

$$\hat{C} = CP \left\{ \frac{e^{-\left| \frac{(X/XP) - 1}{1 - I} \right|^n} - e^{-(1/(1 - I))^n}}{1 - e^{-(1/(1 - I))^n}} \right\}$$

where,

C = coverage in square feet (≥ 2 gal/100 ft²)

CP = coverage peak (scalar for the sigmoid)

$X = (1250 - H)$

XP = the point in X at which C peaks

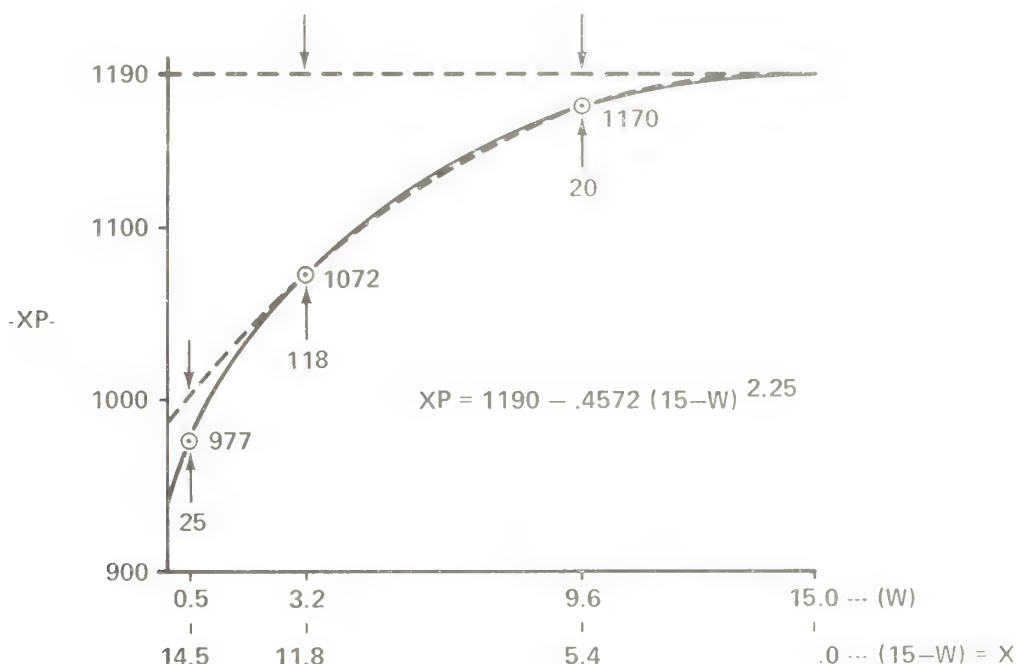
I = the proportional point in X at which the inflection point of the bell-shaped curve occurs (a) in the range $X = 0$ to XP for the left half of the curve or (b) in the range $(2XP - X)$ for the right half (fig. 30)

n = the power of the transform that dictates the degree of curvature above and below any inflection point.

Since the XP - and CP - values read from the three curves in figure 27 varied with wind in accord with expectation, they were each expressed as a suitable function of wind by using Matchacurve-1 and -2 techniques.

XP - and CP -values from the foregoing equations along with representative X - and C -values read from one side of the XP for each bell-shaped curve were scaled to the Standard curves in Matchacurve-1. Standards suitably similar to the scaled data curves were identified, and the corresponding n (held constant) and I -values were recorded. Varying over wind in accord with expectation, " I " was described as a function of wind to complete the inputs to the coverage estimator. The details of these computations follow:

Paired W- and XP-values (0.5, 977; 3.2, 1072; and 9.6, 1170) were plotted in figure 30. These points were plotted and a smooth curve was drawn through them (fig. 31) that extended over the relevant range of W (0-15 mi/h).



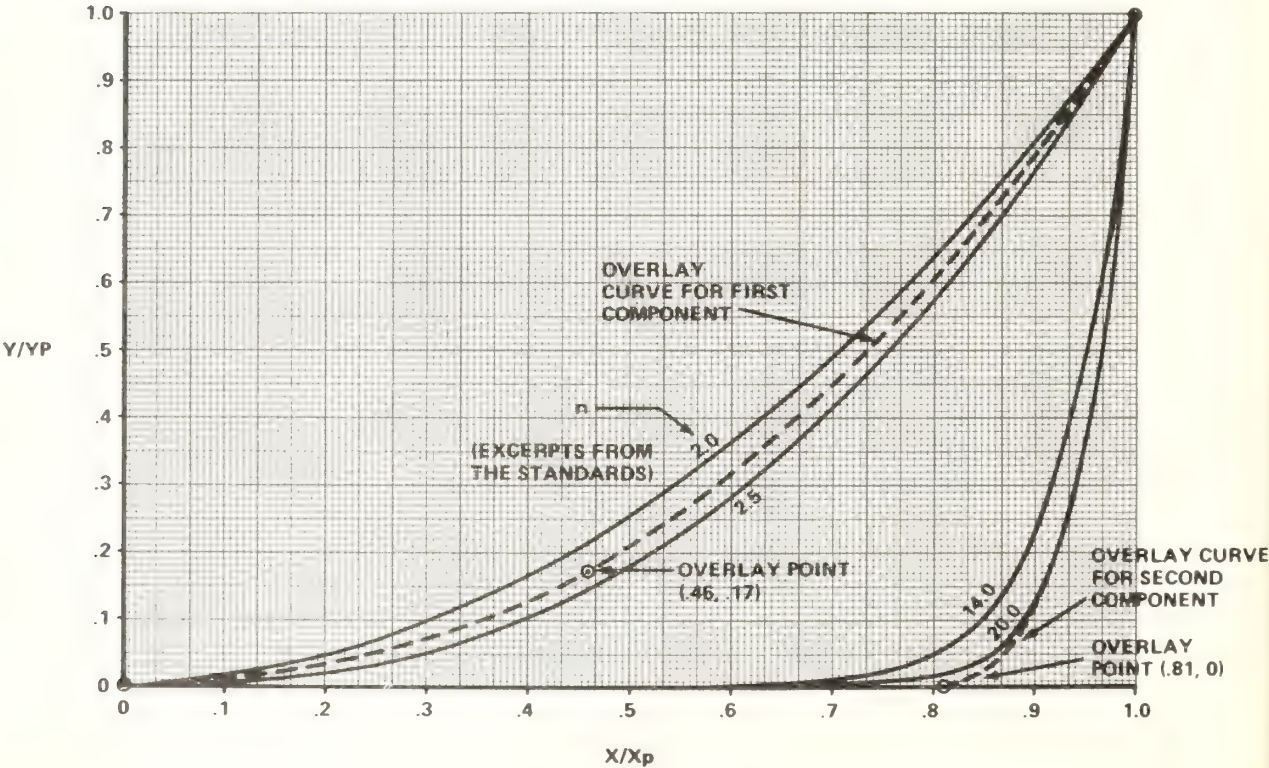
The initial descriptor approach here was to subtract a single-component exponential curve on the reversed W-scale from the intercept, 1190. W was reversed in $X = (15-W)$ to align large values of the independent variable with those of XP. Next, the three data point X-values and associated coverage differences (absolute) from 1190 were scaled to 1.0 at $X = 14.5$. An overlay curve was plotted for Matchacurve-2, but was not well matched by any curve in sets A-1, A-2, or A-3 of the Standards; so a two-component approach was adopted. This time, the differences were fitted at $X = 0, 5.4$, and 11.8 to start with (see the dotted line below the intercept, 1190, in figure 31). Then, the difference (0.25) between the first curve and the desired curve (for $11.8 \leq X \leq 14.5$) was added as a second component. Computations are summarized in table 6 and overlay curves are shown in figure 32.

Table 6

W	XP	(15-W), X	(X/11.8)	(1190-XP), Y	Y/118	$(b_1X^{2.25})^{1/}$
0.0	--	15.0	--	--	--	--
.5	977	14.5	--	213	--	188
3.2	1072	11.8	1.00	118	1.00	118
9.6	1170	5.4	.46	20	.17	20
15.0	1190	.0	.00	0	.00	0

X	X/14.5	$(Y-b_1X^{2.25}),$ d	d/25	$(b_2X^{20})^{2/}$	$\hat{XP}^{3/}$
15.0	--	--	--	--	936
14.5	1.00	25	1.00	25	977
11.8	.81	0	.00	0	1072
5.4	.37	0	.00	0	1170
.0	.00	0	.00	0	1190

- 1/ $b_1 = 118/(11.8)^{2.25} = 0.4572$
- 2/ $b_2 = 25/(14.5)^{20} = 1.4811 \times 10^{-22}$
- 3/ $\hat{XP} = 1190 - b_1X^{2.25} - b_2X^{20}$ --which gives a perfect match for the original XP-values at control points 0-14.5 in wind.



A-1. — Standards for position A, set 1 — (X-transform to be fitted by least squares = $(X)^n$, $0 < X \leq X_p$)

Figure 32

The completed function was then:

$$XP = 1190 - 0.4572 (15-W)^{2.25} - 1.4811 \times 10^{-22} (15-W)^{-1.1}, \quad 0 \leq W \leq 15$$

Figure 33

Paired W- and CP-values (0.5, 8900; 3.2, 8100; and 9.6, 6970) were read from figure 30. These points were plotted and a smooth curve drawn through them (fig. 33) that extended over the relevant range of wind, 0-15 mi/h.

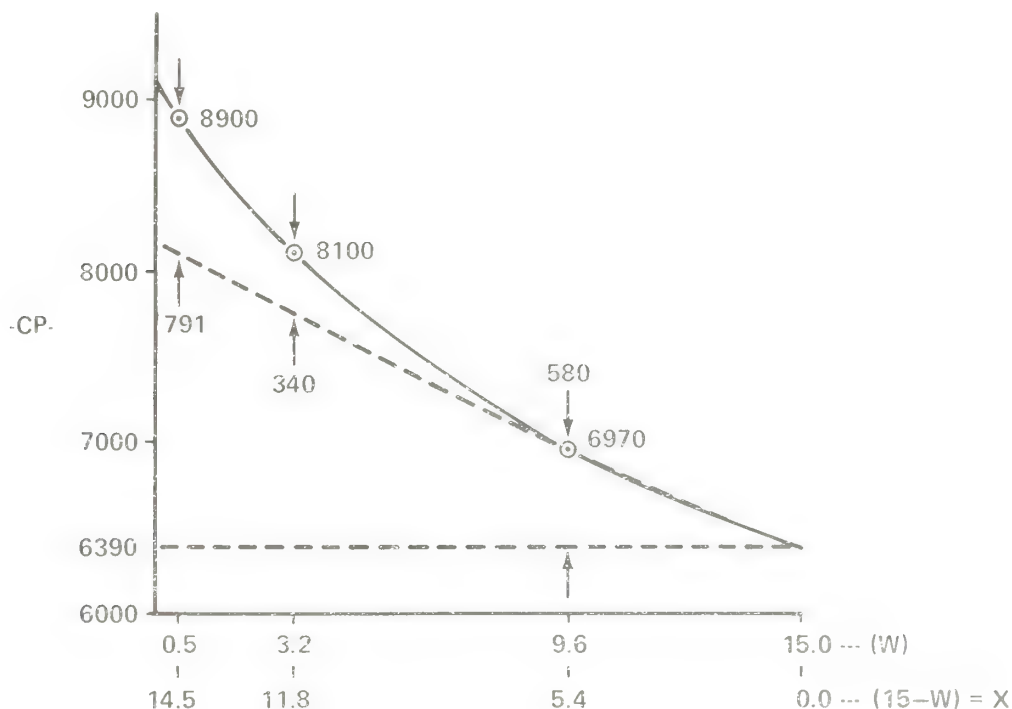


Figure 33

Again, a single-component exponential was first tried for the descriptor here. Reversing the W-axis to $X = (15-W)$ to align large values of the independent variable with those of CP, the X- and CP-values were scaled to 1.0 at $X = 14.5$. An overlay curve was constructed and compared to the Standards of Matchacurve-2. But, none of the Standards were acceptably close to the overlay; so a two-component model was tried next.

To start with, the lower end of the curve ($0.0 \leq X \leq 5.4$) was fitted with an intuitively selected flat form ($X^{1.1}$); it was obvious without scaling and overlays that the curve was extremely flat in that range of X (fig. 33). The $X^{1.1}$ was then the difference (580) between the intercept (6390) and the desired curve height (6970) at $X = 5.4$; so the first component, a partial descriptor for CP, was:

$$CP = 6390 + (580)(5.4)^{1.1} \quad 0 \leq X \leq 5.4$$

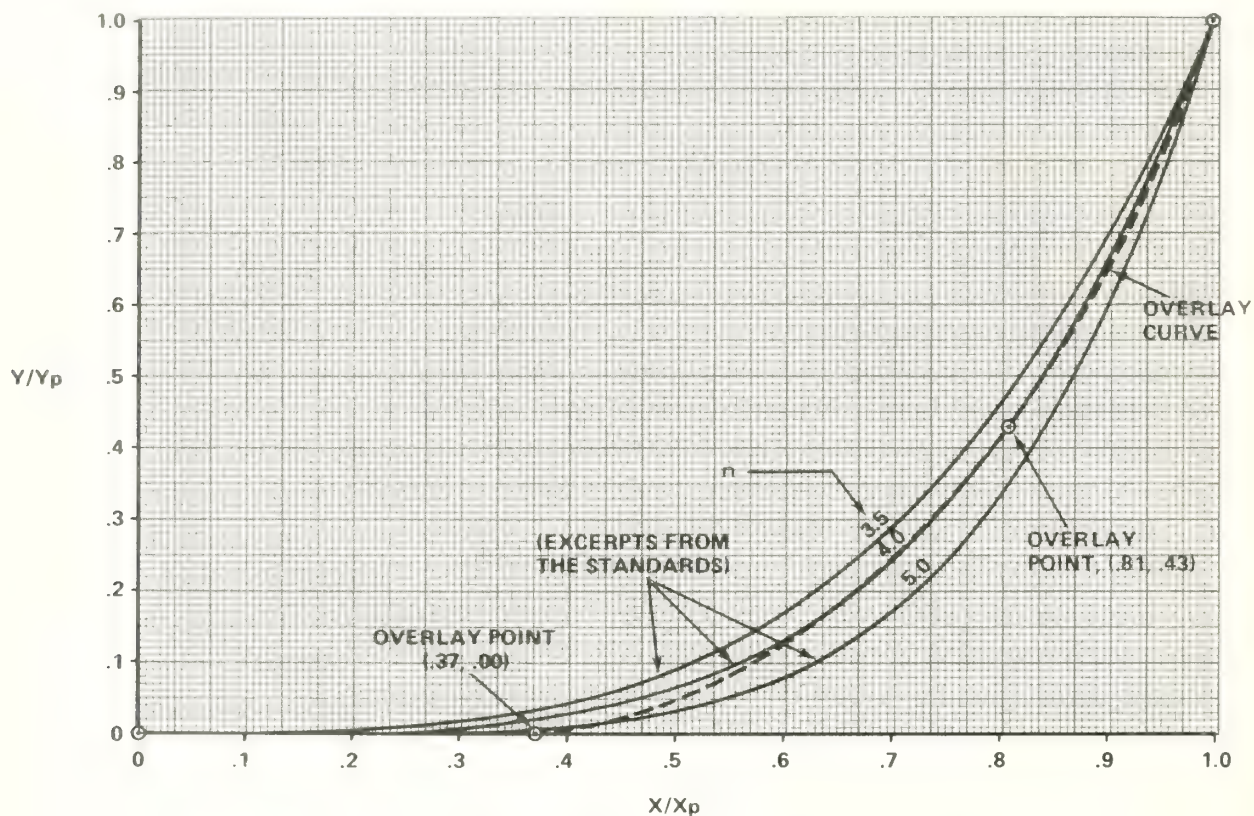
This is the dashed line above the intercept (6390) in figure 33. The remaining differences, 340 and 791, and the associated X-values were then scaled to 1.0 at $X = 14.5$ (table 7).

Table 7

W	X = (15-W)	(X/14.5) ^{1/}	difference, d	d/791 ^{1/}
0.0	15.0	--	--	--
.5	14.5	1.00	791	1.00
3.2	11.8	.81	340	.43
9.6	5.4	.37	0	.00
15.0	.0	.00	0	.00

^{1/} Proportions for overlay curve.

The paired proportions were then plotted, an overlay curve drawn, and the latter compared to set A-1 of the Matchacurve-2 Standards (fig. 34).



A-1. — Standards for position A, set 1 — (X-transform to be fitted by least squares = $(X)^n$, $0 \leq X \leq X_p$)

Figure 34

The Standard curve with $n = 4.0$ matched the overlay fairly well. So the fourth power of X was scaled to the difference, 791, at $X = 14.5$ and added to the partial function already in hand. Then, the complete function was:

$$\begin{aligned}
 CP &= 6390 + (580/(5.4)^{1.1})(15-W)^{1.1} + (791/(14.5)^4)(15-W)^4 \\
 &= 6390 + 90.739 (15-W)^{1.1} + 0.017894 (15-W)^4, \\
 0 \leq X &\leq 15
 \end{aligned}$$

where the computations are as summarized in table 8:

Table 8

W	CP	(15-W), X	(X/5.4)	(CP-6390), Y	(Y/580)	$(b_1X^{1.1})^{1/}$
0.0	--	15.0	--	--	--	--
.5	8900	14.5	--	2510	--	1719
3.2	8100	11.8	--	1710	--	1370
9.6	6970	5.4	1.00	580	1.00	580
15.0	6390	.0	.00	0	.00	0

X	(X/14.5)	$(Y-b_1X^{1.1}),$ d	(d/791)	$(b_2X^4)^{2/}$	CP ^{2/}
15.0	--	--	--	--	9080
14.5	1.00	791	1.00	791	8900
11.8	.81	340	.43	347	8107
5.4	.37	0	.00	15	6985
.0	.00	0	.00	0	6390

- 1/ $b_1 = 580/(5.4)^{1.1} = 90.739$
- 2/ $b_2 = 791/(14.5)^4 = 0.017894$
- 3/ $\hat{CP} = 6390 + b_1X^{1.1} + b_2X^4$. These are sufficiently close to the original CP-values for our purposes.

Matching Bell-Shaped Curves

Tables 9-11 list XP- and CP-values from the equations developed in the foregoing sections along with some representative X- and C-values from either side of the XP-values for the three curves in figure 30. Also listed are C-value estimates obtained by using matching e-transforms from Matchacurve-1 Standards (see the overlay curve in figure 35).

Table 9

W	H	(1250-H), (2XP-X), ^{1/}		(K/977)	C	(C/8900)	$\hat{C}^{2/}$
		X	K				
0.5	50	1200	754	0.772	6860	0.771	7137
	100	1150	804	.823	7800	.876	7793
	150	1100	854	.874	8450	.949	8322
	200	1050	904	.925	8770	.985	8692
	273	<u>977</u> ^{3/}	<u>977</u>	1.000	<u>8900</u> ^{3/}	1.000	8900

^{1/} Temporary transform for plotting the overlay curve only. The X-values need to be in ascending order toward XP = 977.

^{2/} Estimated coverage using the e-transform with CP = 8900, XP = 977, I = 0.510, n = 2.0, and a zero intercept.

^{3/} Smoothed values from the XP- and CP-estimators, each a function of wind (shown earlier in the text).

Table 10

W	H	(1250-H), (2XP-X),		(K/1072)	C	(C/8107)	$\hat{C}^{1/}$
		X	K				
3.2	50	1200	944	0.881	6730	0.830	6843
	100	1150	994	.927	7600	.937	7612
	150	1100	1044	.974	8040	.992	8042
	178	<u>1072</u>	<u>1072</u>	1.000	<u>8107</u>	1.000	8107

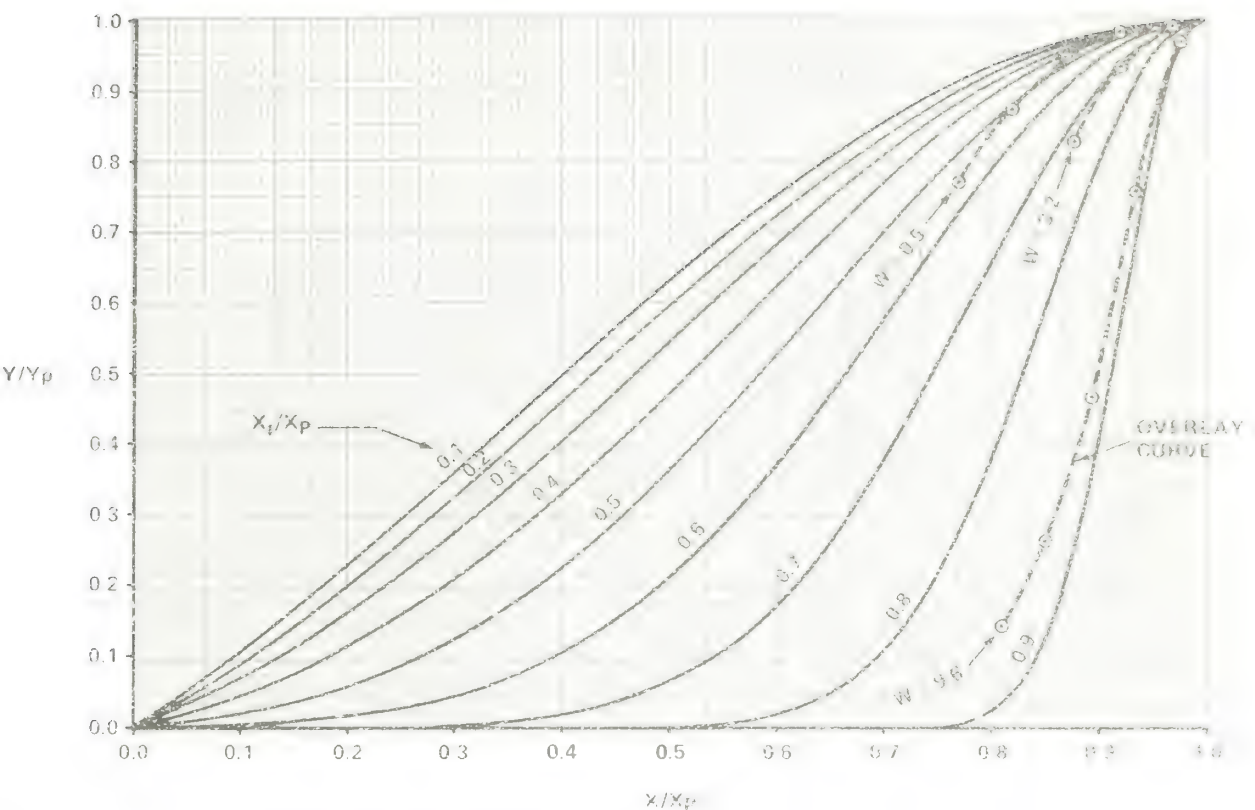
^{1/} Estimated coverage using the e-transform, CP = 8107, XP = 1072, I = 0.710, n = 2.0, and a zero intercept.

Table 11

W	H	(1250-H), ^{1/}		C	C/6985	$\hat{C}^{2/}$
		X	(X/1170)			
9.6	80	<u>1170</u>	1.000	<u>6985</u>	1.000	6985
	100	1150	.983	6820	.976	6845
	150	1100	.940	5300	.759	5448
	200	1050	.897	3270	.468	3364
	250	1000	.855	1830	.262	1612
	300	950	.812	997	.143	600

^{1/} Since the right half of this curve (fig. 30) was read, X-values are already ascending toward XP = 1170 and no transform of X is necessary for plotting the overlay curve.

^{2/} Estimated coverage using the e-transform, CP = 6985, XP = 1170, I = 0.880, n = 2.0, and a zero intercept.



Set 2. - Standards for $n = 2.0$ and scaled inflection points X_I/X_P , ranging from 0.1 to 0.9

As may be seen in tables 9, 10, and 11, the coverage values of each curve were scaled to 1.0 by using the appropriate CP as the maximum. The values of X or of $(2XP-X)$ were similarly scaled by using the appropriate XP as the maximum. After the paired proportions for H -levels within W -levels were plotted and smoothed as three overlay curves, they were compared to the Matchacurve-1 Standards for $n = 2$ (fig. 35).

Although better matches for some of these overlays can be found in Standards that have n other than 2.0, it was decided to hold n constant over wind to avoid sur- irregularities that may develop when both n and I are allowed to vary. Then, the I -values (X_I/X_P in the Standards), corresponding to the best matching curve alternatives in this set, were estimated to be 0.50, 0.70, and 0.88 for $W = 0.5$, 3.2, and 9.6, respectively. On scaling and checking these and alternative curves (by means of a small computer) at the tabled H -values by W -group, some improvement was achieved with the final I -array, 0.51, 0.71, and 0.88. The last column in each of tables 9-11 shows the final scaled coverage estimates. There was close proximity of these values to actual coverage, C , so $I = f(W)$ was next developed.

For $I = f(W)$

Using the paired wind and I -values just determined (0.5, 0.510; 3.2, 0.710; and 9.6, 0.880), " I " was plotted over W and a smooth "initial" curve drawn through the three data points (fig. 36).

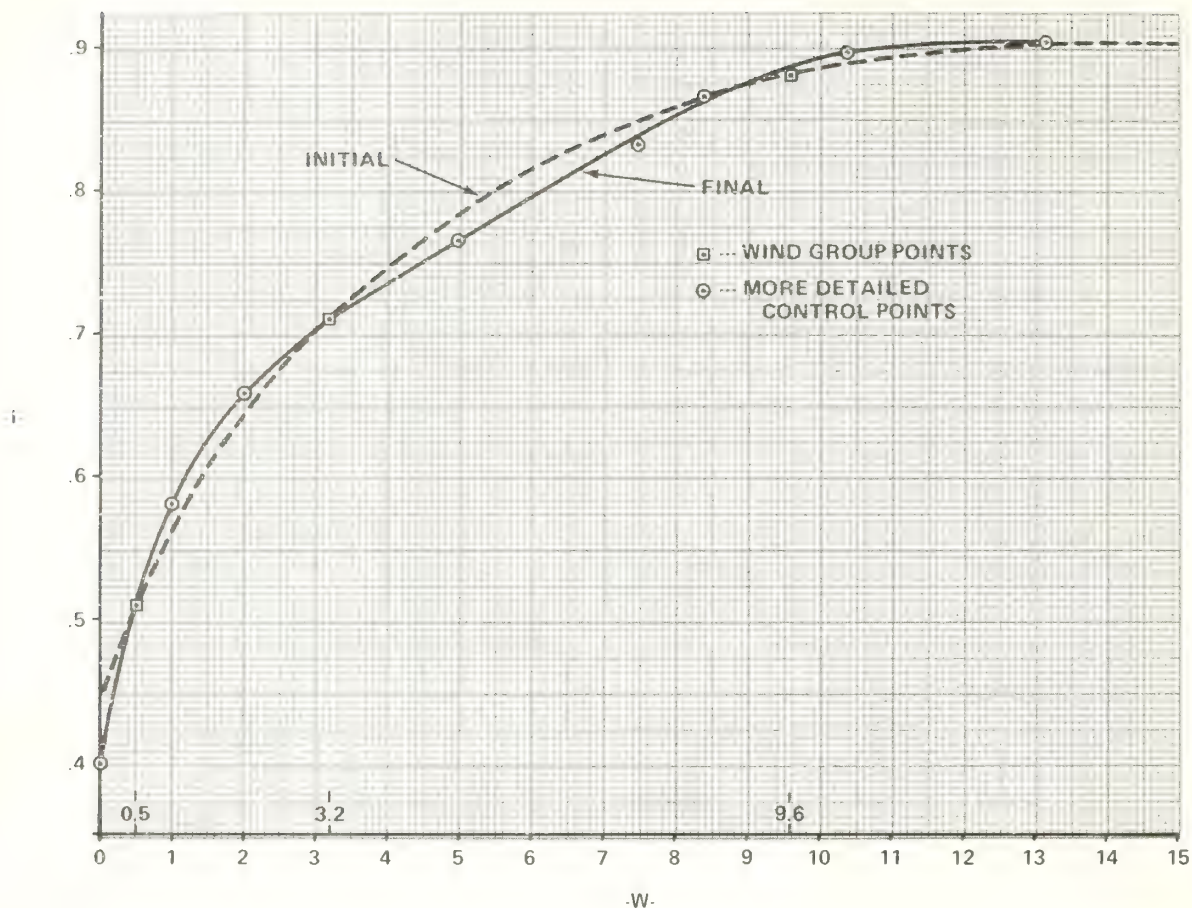


Figure 36

On checking the performance of the e-transform over the range of W , with smoothed CP-, XP-, and initial I-values, it was found that the left edge of the surface undulated unacceptably. Further, performance in the high-wind group was not well balanced for the relatively divergent wind levels there (6.4, 8.4, 10.4, 13.2). These problems were largely overcome by iteratively adjusting to the "final" curve in figure 36. This was the one for which a descriptor was developed.

This curve was judged to be a multicomponent model because neither the sigmoids nor the exponentials have the flattened central segment found there. Since a suitable single-component exponential was not found, the flat segment was represented by a straight line; the negative differences at the left end by an exponential; and those at the right by a portion of a sigmoid (fig. 37).

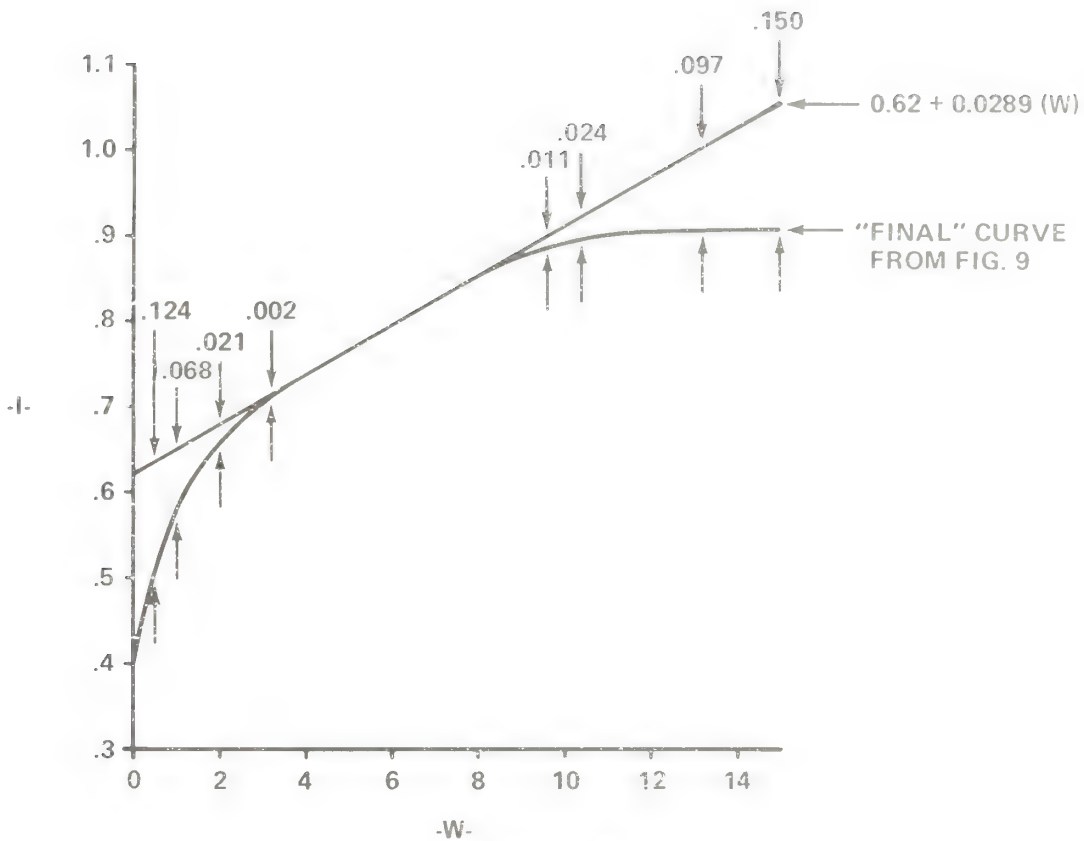


Figure 11

The Flat Segment: A straight line was drawn along the "final" curve. The intercept, 0.62, and values necessary to the coefficient for W, $(1.054 - 0.620)/15 = 0.0289$, were read directly from the graph.

The Left End: This portion of the curve was satisfactorily matched by a single exponential of the reversed W-axis, scaled at $W = 14.5$ (table 12).

Table 12

W	(15-W), X	$(X/14.5)^{1/}$	I	$(0.62 + 0.0289 W), (Y_1 - I),$ Y ₁	d	$(d/0.124)^{1/}$	$(b_2 X^{16.75})^{1/}, d$
0.0	15.0	--	0.400	0.620	0.220	--	0.219
.5	14.5	1.00	.510	.634	.124	1.00	.124
1.0	14.0	.97	.581	.649	.068	.55	.069
2.0	13.0	.90	.657	.678	.021	.17	.020
3.2	11.8	.81	.710	.712	.002	.02	.004

^{1/} Proportions for an overlay curve that is not presented here in the text.

^{2/} $b_2 = 0.124/(14.5)^{16.75} = 4.3703 \times 10^{-21}$. The d-values are sufficiently close to the original d-values for our purposes.

So the partial form at this point:

$$\hat{Y} = 0.62 + 0.0289 (W) - 4.3703 \times 10^{-21} (15-W)^{16.75}$$

The Right End: For this portion of the curve, the differences, Y_2 , from the straight line and associated scaling information are listed in table 13.

Table 13

W	(W/15) ^{1/}	I	0.62 + 0.0289(W), (Y ₁ -I),		
			Y ₁	Y ₂	(Y ₂ /0.15) ^{1/}
8.4	0.56	0.863	0.863	0.000	0.00
9.6	.64	.886	.897	.011	.07
10.4	.69	.897	.921	.024	.16
13.2	.88	.904	1.001	.097	.65
15.0	1.00	.904	1.054	.150	1.00

^{1/} Proportions for overlay curve, scaled to 1.00 at W = 15.0 (fig. 38, right side).

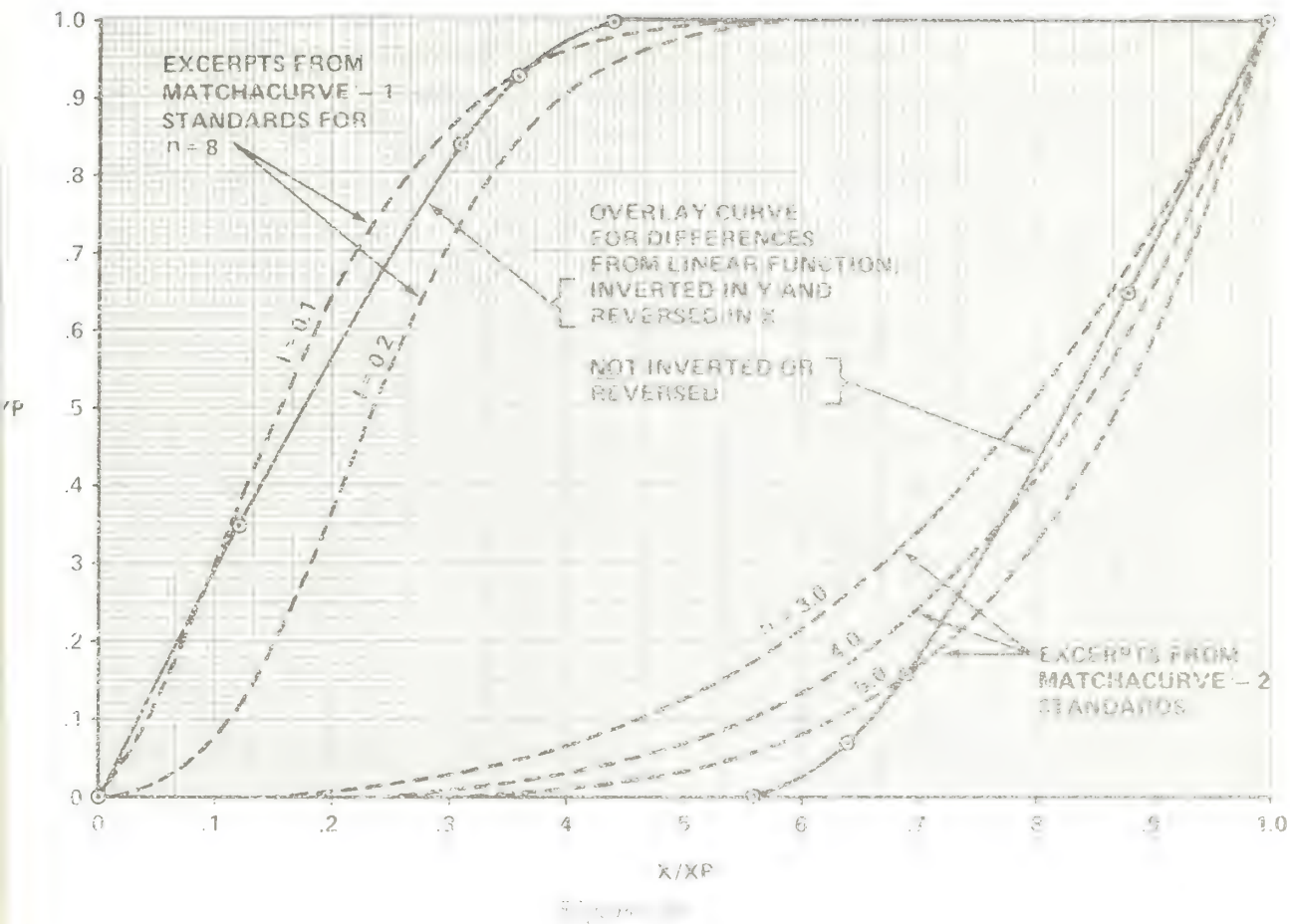
Since the curve of Y_2 over W is concave upward with increasing wind, both single- and double-component exponential functions were examined as potential descriptors for this curve, but none were suitably accurate. However, by reorienting the exponential curve in space, reversing W to (15-W) and inverting Y_2 to (0.15- Y_2), the curve becomes convex upward with increasing values of (15-W). Also, it is at least roughly matched by the sigmoid Standard, n = 8 and I = 0.108 (see table 14 and the left overlay curve in fig. 38). This sigmoid was the result of an interpolation between the two Standards I = 0.1 and 0.2 at n = 8.

Table 14

W	(15-W),		Y ₂	(0.150-Y ₂),		(0.150 e ^{-T}), ^{2/}
	X	(X/15) ^{1/}		Y ₃	(Y ₃ /0.150) ^{1/}	$\hat{Y}_3$
0.0	15.0	1.00	0.000	0.150	1.00	0.150
8.4	6.6	.44	.000	.150	1.00	.146
9.6	5.4	.36	.011	.139	.93	.139
10.4	4.6	.31	.024	.126	.84	.130
13.2	1.8	.12	.097	.053	.35	.053
15.0	.0	.00	.150	.000	.00	.000

^{1/} Proportions for overlay curve, scaled to 1.00 at X = 15 (fig. 38, left side).

^{2/} The scaled e-transform with n = 8, I = 0.108, XP = 15, and intercept = zero.



Then, the right end was specified as:

$$0.15 - Y = 0.150 \text{ e-transform, based on } x = (15-w)$$

or

$$Y_2 = 0.150 - 0.150 \text{ e-transform,}$$

and

$$Y_2 = 0.150 - 0.150 \left\{ \frac{\left| \frac{(15-w)}{15} - 1 \right|^e}{\left| \frac{1}{1 - 0.108} \right|^e} - \left| \frac{1}{1 - 0.108} \right|^e}{1 - e^{-\left| \frac{1}{1 - 0.108} \right|^e}} \right\}$$

When all three components were assembled for I:

$$I = 0.62 + 0.0289 (W) - 4.3703 \times 10^{-21} (15-W)^{16.75}$$

$$- \left\{ 0.15 - 0.15 \left\{ \frac{e^{-\left| \frac{(15-W)}{15} - 1 \right|^8}}{0.892} - 0.08249 \right\} \right\} \right\} , 0 \leq W \leq 15$$

This form can be simplified further as shown on page 37.

Estimated I-values are listed in the following tabulation:

<u>W</u>	<u>I</u>	<u>$\hat{I}$</u>
0.0	0.400	0.401
.5	.510	.510
1.0	.581	.580
2.0	.657	.658
3.2	.710	.709
5.0	.766	.764
7.5	.838	.835
8.4	.863	.859
9.6	.886	.886
10.4	.897	.900
13.2	.904	.905
15.0	.904	.904

where I and $\hat{I}$ were suitably close over the range of W.

At this point, all necessary inputs had been derived and the complete descriptor was:

$$C' = CP \left\{ \frac{e^{-\left| \frac{(X/XP) - 1}{1 - I} \right|^{2.0}} - (1/(1-I))^{2.0}}{1 - e^{-(1/(1-I))^{2.0}}} \right\}$$

where:

C' = coverage in square feet, estimated from the pre-least squares fit model

CP = coverage peak for any specified windspeed, W, or

$$CP = 6390 + 90.739 (15 - W)^{1.1} + 0.017894 (15 - W)^4, \quad 0 \leq W \leq 15$$

$$X = (1250 - H)$$

H = drop height, $50 \leq H \leq 300$

XP = point in X at which CP occurs, or

$$XP = 1190 - 0.4572 (15 - W)^{1.5} - 1.4811 \times 10^{-3} (15 - W)$$

I = inflection point in X expressed as a proportion of

$$XP \text{ (XI/XP in Matchacurve-1),}$$

and

$$I = 0.4565 + 0.0289(W) - 4.5703 \times 10^{-4} (15-W)^{1.5} \\ + 0.16349 e^{-\left| \frac{\left(\frac{15-W}{15} - 1 \right)}{0.892} \right|^8}$$

Note that the last component has been simplified (see page 36).

Then, fitting this form back to the original 16 observations by least squares in a simple linear model forced through the origin

$$\bar{C} = bC' = \text{least-squares estimate of coverage}$$

where:

$$b = \frac{CC'}{(C')^2} \text{ over the 16 observations}$$

The final model is:

$$C = 1.000569(C')$$

$$\text{with } \bar{C} = 6962 = \text{mean coverage}$$

$$s_{y \cdot x} = 850 = \text{standard error of estimate}$$

$$R^2 = 0.89 = \text{coefficient of determination}$$

The coefficient, b, is very near 1.0000; so it is evident that even before least-squares adjustment, the original descriptor was well aligned with the data spacially. But, in checking the form of the descriptor by comparing predicted and actual coverage (fig. 39), at least one anomaly appears. The three high-wind points probably lie close to the surface since greater variation occurs about the surface at lower wind levels; i.e., reasonable variance about the surface would be expected at high-wind levels also. The accuracy of the standard error of the estimate shown, 850, cannot be assessed since an unknown number of degrees of freedom have been sacrificed by developing the detailed curve-form hypothesis on the data set from which the estimate was made.

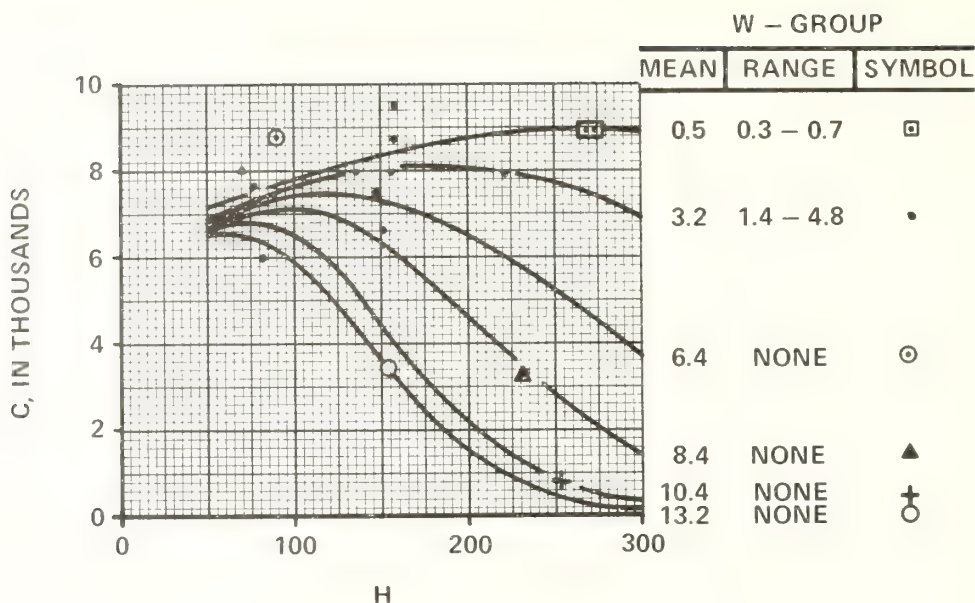
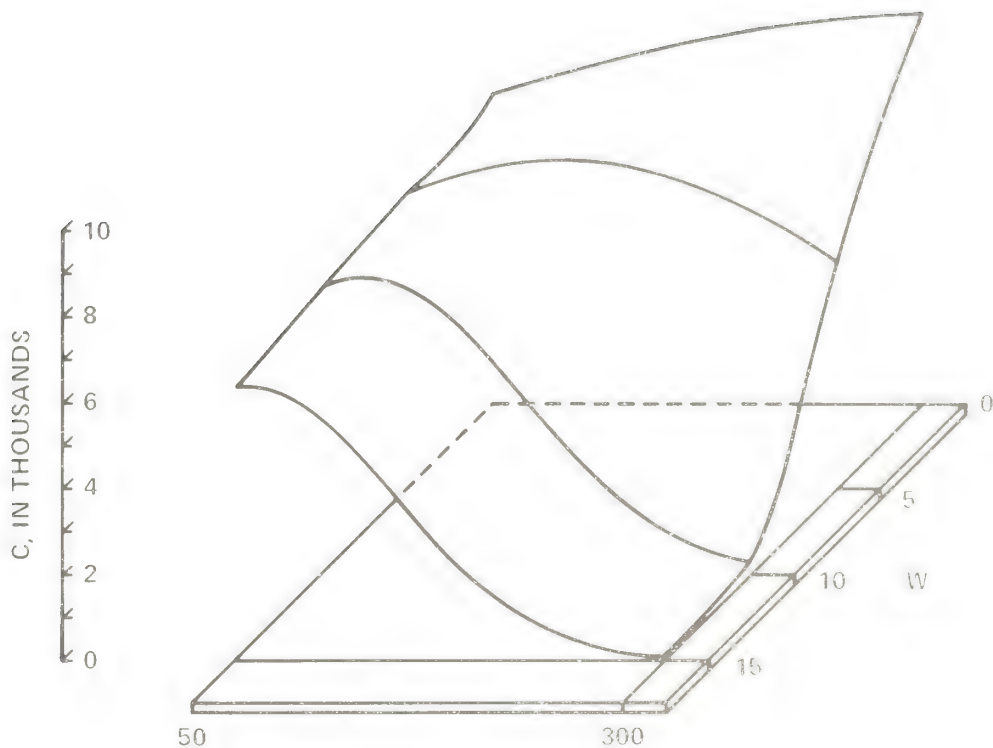


Figure 39

Recall that through the use of controlled I-values (fig. 36) for curves passing close to the three high-wind points, low variation of these points from the surface was assured. Alternative I-values could be used that would allow for variation from the surface, in accord with some assumed variance criteria. This refinement was not undertaken and the model was adopted as developed. Predicted values (table 15) and the associated surface (fig. 40) for the model are as follows:

Table 15

Wind (mi/h)	Drop height (feet)					
	50	100	150	200	250	300
0	7198	7804	8316	8710	8969	9081
5	6830	7525	7707	7337	6491	5338
10	6617	6707	4925	2619	1009	282
15	6345	5663	3460	1447	414	81



H.

Figure 40

Since the objective of this paper is to show the analyst a system that can be used to exercise a great deal of curve-form control in model development, it is appropriate to review the imposing list of constraints that can be met in models like this one. Controllable items include: the intercept for the whole surface; the elevation, breadth, and positioning of the peaks over the interacting independent variables; the trend in Y at the truncated left edge of the surface; the magnitude of curvature above and below the inflection points in the bell-shaped curves; and the positioning of the inflection points themselves within the ranges of the independent variables.

Four or More Dimensions

Descriptor procedures outlined for three dimensions can be extended to more dimensions. For example, given that we have a set of 4-D graphs, Y over X_1 , at four points in X_2 and that each such set occurs at three points in X_3 (fig. 4, page 4). Assume also that we have developed 2-D descriptors for these 12 curves.

The corresponding 12 intercepts, scalars, and X_1 -transform parameters (call this group of variables K_i) may vary systematically over X_2 and X_3 . So treat each K as a 3-D relation, ($K = f(X_2, X_3)$). Plot it over X_2 and fit a smooth curve through the resulting points at each of the specified levels of X_3 . Identify a suitably accurate descriptor for each curve:

$$K = \text{intercept} + \text{scalar} (X_2\text{-transform})$$

Now, express the intercepts, scalars, and X_2 -transform parameters (K_i) of *these* curves as functions of X_3 and compile the 3-D descriptors by substitution in the basic X_2 -descriptor above:

where:

$$\begin{aligned}\text{intercept} &= f_a(X_3) \\ \text{scalar} &= f_b(X_3) \\ X_2\text{-transform} &= f(P_j), \text{ and} \\ P_j &= f_j(X_3)\end{aligned}$$

The resulting K_i are then inputs to the 2-D, X_1 -descriptor:

$$Y = \text{intercept} + \text{scalar} (X_1\text{-transform})$$

where:

$$\begin{aligned}\text{intercept} &= f_c(X_2, X_3) \\ \text{scalar} &= f_d(X_2, X_3) \\ X_1\text{-transform} &= f(P_j), \text{ and} \\ P_j &= f_j(X_2, X_3)\end{aligned}$$

The expansion of the system to five or more dimensions is analogous and the amount of descriptor development increases exponentially with the dimensions. This is the cost of more complete curve-form control and is a factor to consider in selecting one descriptor process from the array of alternatives.

LIMITATIONS

The descriptor developed for a specific relationship by using the procedures outlined here is likely to be more complex algebraically than one developed from limited, standardized transformations,--fairly popular at present. However, to the analyst who has access to at least a small desk-top computer, the added computational complexity is literally of no consequence. Such a computer is a minimum requirement for the application of Matchacurve procedures.

Some new, but certainly not insurmountable, problems of communicating through reports and publications *are* created. Complex descriptors are not easily translated into spacial characteristics, often vital for reader comprehension. The solution to this problem is to *devote suitable discussion* to the shapes and magnitudes of trends and to the limits of application. To sidestep a potentially impossible task of hand calculation by the reader, tables of computer-calculated values may be included for pertinent levels of the independent variables. Rough interpolation, if required, can be left to the reader.

In reality, when graphic forms are developed from data, the effects of variables incorporated in the model are being scaled visually by the analyst. Then, as is shown, he makes further visual scale selections in quantifying this model mathematically. A simple linear, least-squares adjustment of the entire model to some pertinent data set (where available) helps to identify scales more objectively. By way of contrast, a mechanized fitting process, such as least squares, could be substituted for the *scaling* portion of the system and some benefits could accrue in the overall fitting effort.

However, the practicality of this alternative is lessened in the presence of the complex, nonlinear (in the parameters) mathematical models that often result from application of the Matchacurve procedures. Estimating the parameters for such models requires the use of rather specialized fitting techniques (Hartley 1961; Spang 1962; Marquardt 1963) and, quite possibly, mathematics beyond the average practicing analyst. Marquardt's iterative system seems to be the most acceptable, but no system appears to be universally applicable (Draper and Smith 1966).

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1973. MATCHACTRIVE-3: multiple-component and multidimensional mathematical models for natural resource studies. USDA For. Serv. Res. Pap. INT-146, 42 p., illus. Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.

Mathematical model development procedures for graphed relations between variables are presented. As an extension of single-component two-dimensional model alternatives given in the two previous papers of the Matchcurve series, the author concentrates on multiple-component and multidimensional modeling. These procedures are particularly useful in describing unique main effect- and interaction-. A detailed application is given for a heavily convolute surface developed from "live" data.

KEYWORDS: model, interaction, mathematical, descriptor.

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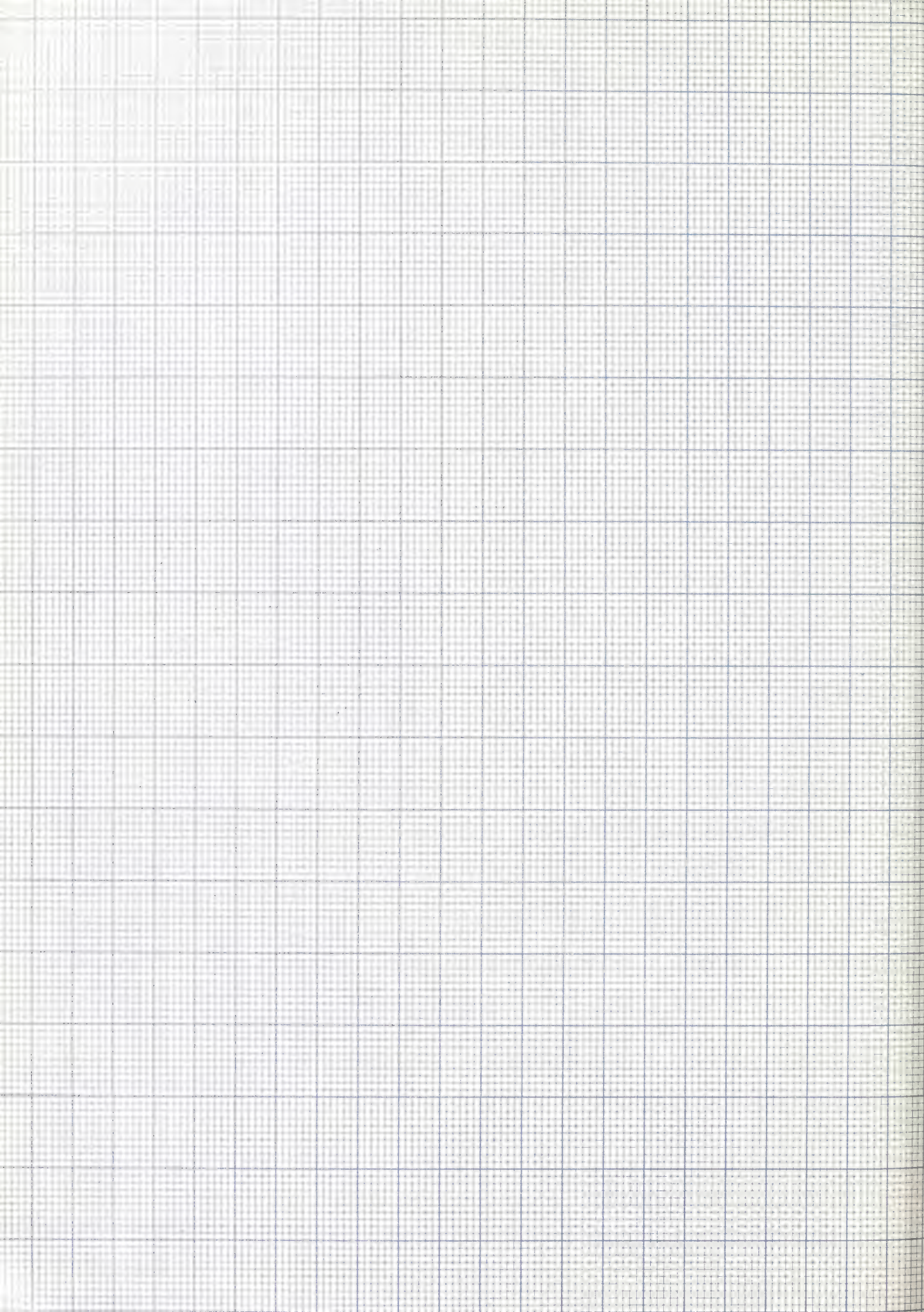
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Logging Equipment, Methods, and Cost for Near Complete Harvesting of Lodgepole Pine in Wyoming

R. B. Gardner and W. S. Hartsog



USDA Forest Service Research Paper INT-147, 1973
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Robert W. Harris, Director

The Authors

RULON B. GARDNER is Principal Research Engineer stationed at the Forestry Sciences Laboratory in Bozeman, Montana. He has been involved with logging and forest road construction for the Forest Service in various capacities for 18 years--the past 10 years in a research capacity.

WILLIAM S. HARTSOG is a Research Engineer, Forest Engineering Research, stationed at the Forestry Sciences Laboratory in Bozeman, Montana. He has been involved with logging and forest roads on various assignments for 5 years.

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Abstract

Lodgepole pine (Pinus contorta Dougl.) in Wyoming was logged to near complete standards using a feller-buncher, grapple and choker rubber-tired skidders, and a portable chipper. Cost of removing the commercial timber was comparable to costs incurred in conventional harvesting. Cost of removing the logging residue and chipping it on the site shows promise for future utilization. A more efficient logging system is simulated and proposed for reducing the costs of near complete harvesting in the future.

Introduction

A cooperative study of the economic feasibility and environmental impacts of near complete harvesting of lodgepole pine (*Pinus contorta* Dougl.) in the Union Pass area, Teton National Forest, Wyoming, was begun in the summer of 1971. The cooperators are the USDA Forest Service, Intermountain Forest and Range Experiment Station, Intermountain Region; and Champion International. The logging was completed in the fall of 1971. A report on the initial findings of this study was published in April 1972 as an Intermountain Forest and Range Experiment Station Research Note (USDA Forest Service Research Note INT-160, "Utilization of Lodgepole Pine Logging Residues in Wyoming Increases Fiber Yield"). It reported that fiber yields were increased by 35 percent using near complete harvesting standards.

This report discusses the equipment, methods, and costs of logging in this study area. The effects of these logging methods on regeneration, nutrient cycling, hydrology, wildlife, esthetics, and overall costs and benefits will be reported as data become available and are evaluated.

Description of Logging Units

Two blocks, each about 40 acres, were laid out in similar stands of lodgepole pine. One half of each block, designated a cutting unit, was harvested to conventional clear-cutting standards, the other half was harvested to "near complete" standards. The cutting units, numbered 1 through 4, totaled approximately 80 acres (fig. 1). Conventional harvesting called for the removal (as logs) of all merchantable trees with a minimum top diameter of 6 inches. The near complete standards included, in addition to removal of logs, the chipping of the tops and limbs of all merchantable trees, all remaining live and standing sound dead trees 3 inches d.b.h. and larger, and all sound down material over 6 inches in diameter at the large end and longer than 6 feet. As previously reported, removal of this material increased fiber yield by 35 percent and left the site ready for planting without additional cleanup, site preparation, or burning to reduce fire hazards (fig. 2).

A



B



Figure 1. -- A. Mountain slope with snow-covered forest floor. B. Forested landscape with a large body of water in the background.

Logging Methods and Equipment

Since there was no past experience with near complete harvesting, equipment on the market was studied and a logging system was designed that would have good prospects for economic success. The potential market for residues would be for pulp or reconstituted wood products; therefore, logging debris had to be chipped. All residue, including bark, limbs, and needles, was chipped in a portable chipper at the landing (fig. 3). Trees were felled with a feller-buncher (fig. 4) and were skidded with both rubber-tired and crawler skidders (fig. 5). Logs were bucked and limbed with chain-saws at the landing, loaded on trucks with a heelboom loader, and were hauled to mill by contract haulers.

All of the merchantable logs were transported 40 miles to the U.S. Plywood mill at Dubois, Wyoming. Part of the chips produced at the site were used for experimental pulping and particle board manufacture by Champion International and the U.S. Forest Products Laboratory. The remainder will be used for experimental spreading over test plots at the site, or disposed of off site.



Figure 3.--Chipharvestor in operation at landing.



Figure 4.--John Deere 820G skid steer loader.



Figure 5.--John Deere 820G skid steer loader with log grapple.

The equipment used for the near complete harvesting treatment consisted of the following:

Feller-Buncher:

- 1 - Model 40 LC Drott Feller-Buncher

Chipper:

- 1 - Model SL-22 Morbark Chipharvestor

Skidders:

- 1 - Timberjack Grapple Skidder, Model 230D
- 1 - Garrett Treefarmer, Model 21-A (with ESCO Grapple, Model 112)
- 1 - Garrett Treefarmer, Model 21-A
- 2 - Clark Rangers, Model 666

Combination Equipment (skidding, dozing, slash piling):

- 2 - Caterpillar tractors, Model D-6, 9U Series
- 3 - International Tractors, Model TD15B
- 1 - International Tractor, Model TD20C

Loader:

- 1 - Oshkosh Truck, 1951 with Beloit Model L166 Heelboom Loader

The equipment listed above, with the exception of the feller-buncher, chipper, and grapple skidder, was also used to log the conventional harvest units.

Auxiliary Equipment:

- Ford Truck (Mechanic), Model N600, 1967
- Ford Truck (Transport), Model N600, 1968
- Ford Truck (Transport), Model F350, 1969
- Ford Truck (Woods Boss), Model F250FWD, 1968
- Ford Truck (Service), Model N600, 1969

Specifications for the special equipment (feller-buncher, chipper, and grapple skidder) are included in the Appendix.

PART 1:

Logging Production and Costs

Logging production was recorded daily for each piece of equipment (Gross Data). Time was recorded for operational, delay, and down periods. Merchantable volumes were eight-scaled, and nonmerchantable chip volume was measured in cubic feet. A separate piece count was recorded for merchantable and nonmerchantable material handled by the feller-buncher and the skidders.

Production data were converted to cost by using industry's average equipment cost and wage rates for the area. The costs represent only the direct cost of logging and supervision at the field level. Overhead items such as payroll cost, general administration, etc., are not included.

Table 1 summarizes costs and shows the cost of each operation for each unit. Units 1 and 4 were the near complete harvesting units, and units 2 and 3 were the near complete skidding units. Harvest statistics for each unit are shown in table 2.

For this study, the chips were piled at the site for later experimental use. In commercial operation, they would be blown into vans and transported to the mill. The cost of transporting chips is estimated from going rates and is shown in table 3.

The cost of harvesting and delivering merchantable logs to the mill by either method and are primarily influenced by piece size for the felling, bunching, and skidding operations.

Table 1.--Operational cost summary (\$/Mfbm or BDU)

Operation	Harvest units					
	1 (near complete)	4 (near complete)	2 (conventional)	3 (conventional)		
	Mfbm ¹	BDU ²	Mfbm	BDU	Mfbm	Mfbm
Fell & Buck (Merchantable Volume)	\$ 9.40	--	\$ 8.90	--	\$ 7.86	\$ 7.86
Felling (Feller-Buncher)	⁴ (3.50)	\$ 1.96	³ (2.96)	\$ 0.99	--	
Skidding	5.05	5.52	4.11	5.23	7.75	6.00
Landing ⁴ Equipment Cost	--	0.80	--	1.29	--	
Chasing	1.92	--	2.50	--	1.29	0.00
Chipping	--	3.94	--	3.86	--	
Loading	0.96	--	0.66	--	0.85	0.00
Service	0.80	0.24	0.76	0.25	0.48	0.00
Hauling ⁵	12.90	6.48	12.90	6.48	12.90	12.90
Decking and Road Cost	3.81	1.32	2.44	0.88	4.08	1.00
Total						
Merchantable	\$34.82		\$32.27		\$35.21	\$31.00
Chips		\$20.26		\$18.89		

¹ Mfbm = thousand foot board measure.

² BDU = 2,400 lb bone dry unit.

³ Included in total F&B above.

⁴ Used primarily to forward material to chipper.

⁵ Contracted; hauling for 40 miles.

Table 2.--Harvest unit production

Item	Harvest unit			
	1	4	2	3
Size (acre)	16.8	17.2	21.7	22.5
Net merchantable volume (Mfbm/acre)	14.7	15.2	25.1	21.4
Chip weight (BDU/acre)	50.0	45.4	--	--
Average piece size (Logs/Mfbm)	13.7	7.9	15.8	13.4

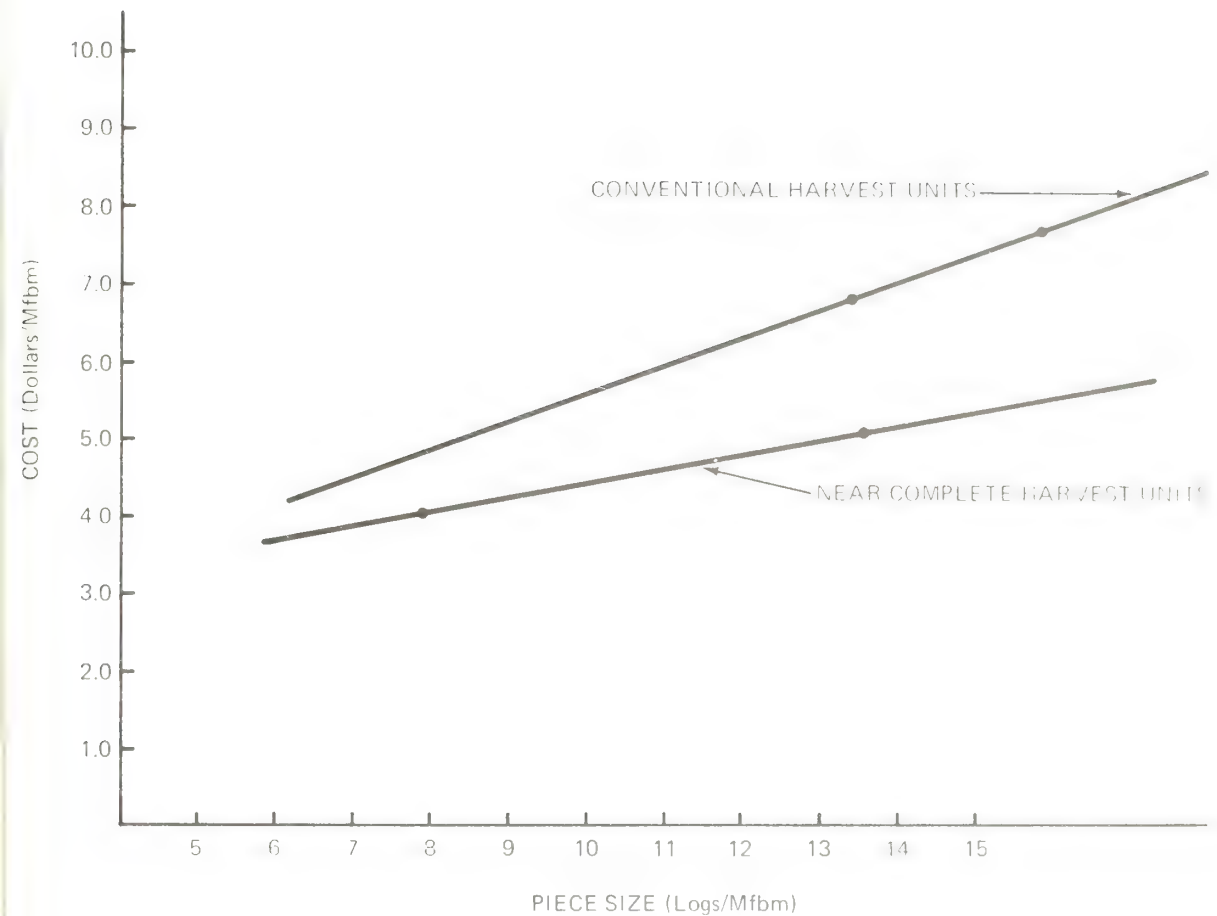


Figure 6.-- Skidding cost versus piece size.

The slope of the curves in figure 6 indicates that in near complete harvesting skidding costs are lower and are less sensitive to piece size than in conventional harvesting. This is mainly because it is more efficient to skid small trees whole than to skid them in pieces. Another possible explanation for reduced cost is that it was not considered practical to remove defects from full trees skidded to the landing. Instead, the entire tree was chipped, which reduced the cost of handling small merchantable logs. (This is also the primary reason for lower merchantable volumes harvested in Units 1 and 4.) Also, in other skidding studies, prebunching of merchantable material has been shown to reduce skidding costs.

The cost of handling and piling the nonmerchantable material (top and limbs) in Units 1 and 4 could be charged against the merchantable volume rather than to the production of BDU's of chips, as was done in this study. Best allocation of these costs can be determined in future sales when and if this level of utilization becomes commercially profitable.

Experience gained from this study and analysis of production capabilities of equipment used for the near complete harvesting units indicates that cost savings could be realized by more careful planning. These possibilities are investigated in Part II.

PART 11:

Recommended Logging Operation for Near Complete Harvesting

As suggested in the conclusion of Part I, costs could probably be lowered significantly by using the most productive equipment for each operation. Table 1 in Part I reports the cost of logging as experienced during the actual operation. In Part II, selecting the most productive units and combining those into a well-scheduled operation gives at least an order of magnitude estimate of possible improvement in cost.

Production Capabilities, Planning, and Scheduling

To simplify the process of system design and scheduling, all fiber units of measurement were converted to bone dry tons (BDT). Table 3 shows the tonnage harvested in both units.

Table 3.--Bone dry tonnage (2,000 lb) by unit

Unit	Merchantable	Nonmerchantable	Total
1	725	1,020	1,745
4	775	936	1,711
Total	1,500	1,956	3,456
Percent	43.5	56.5	100

Table 4.--Hourly operating costs and production capabilities of the equipment.

Equipment	Operation cost including wages	Production capacity ¹	Cost	
			Balanced operation (System I)	Maximum capacity (System II)
	\$ /hr	BDT /hr	\$ /hr	\$ /hr
Drott Feller-Buncher	15.25	25.45	0.600	0.600
Timberjack Grapple				
Skidder	11.26	14.86	.905	.758
Morbark Metro				
Chipharvester	29.50	34.00	1.359	.867
Wheelboom Loader	13.25	23.70	.559	.559
Transport				
Bunks	24.20	5.2	5.410	5.410
Vans	24.26	3.9		
Total			\$8.855	\$5.194

¹Using productive hours only; i.e., deducting idle time.

²See table 5.

Table 4 gives hourly operating costs and production capabilities of the equipment used in a proposed logging operation in dollars and bone dry tons of fiber, respectively. In the last two columns, production in dollars per bone dry ton per hour is given for equipment (operating at the capacity experienced during the study) for a balanced hot logging operation (System I) and a scheduled operation that provides for each equipment type operating at full capacity (System II). Table 5 shows what is meant by a balanced operation--if all of the equipment is moved to the job about the same time, then the entire harvesting operation would produce at the rate of the least productive element. In this case, it would be the feller buncher; i.e., .64 BDT/hr. Table 5 defines the number of units of each class of equipment needed for a balanced logging operation (column 3). In a hot logging operation, all elements of the operation operate simultaneously. In column 5, the percentage of utilization of each class of equipment is shown. Columns 6 and 7 are used for scheduling the equipment on the job as shown in figure 7.

From Table 4, the costs are \$8.85 BDT and \$5.19 BDT for systems I and II, respectively. If these two systems were to operate at 90 percent efficiency, a reasonable goal, then the costs are \$11.02 and \$10.22. These figures are for fuel, landing, and supervision, crew transportation, and service, which are broken down as follows:

Landing \$1.67/BDT

Supervision, Transportation, Service .42/BDT
\$2.09 BDT

These costs must be added to the other costs \$; i.e., \$11.02 + \$2.09 = \$13.11, and \$10.22 + \$2.09 = \$12.31, respectively.

Table 5.--Planning harvesting systems using production capabilities

Equipment	Production capacity	No. units	Production	Percent utilization	Time to harvest both units ¹	Difference from minimum production unit
(1)	(2)	(3)	(4)	(5)	(6)	(7)
	BDT/hr		BDT/hr	Percent	hr	
Drott Feller-Buncher	25.45	1	25.45	100.0	135.5	0
Timberjack Grapple						
Skidder	14.86	2	29.72	85.6	116.0	-19.5
Morbark Metro						
Chipharvester	34.00	1	34.00	42.0	57.5	-78.0
Heelboom Loader	23.70	1	23.70	47.0	63.5	-72.0
Transport						
Bunks	5.2	4	20.80	100.0	72.0	-63.5
Vans	3.9	8	31.20	100.0	62.5	-73.0

¹3,456 BDT from table 3 (1,956 BDT, nonmerchantable - 1,500 BDT, merchantable).

Table 6 summarizes and compares costs for the actual operation in Part I and the two simulated harvesting operations in Part II.

How unit costs compare for the actual operation and the simulated operation, working at maximum capacity (System II), is shown below:

Operation	Merchantable \$/MBM	Nonmerchantable \$/MBM
Actual	33.50	19.81
Simulated (System II)	28.70	16.60

These figures are weighted averages for the near complete harvesting units (1, 4) for both harvesting systems; i.e., the actual and the simulated operations.

Table 6.--Cost summary for harvesting systems

Harvesting system	Cost/BDT	Difference from actual	Difference
	Dollars		(Percent)
Actual	¹ \$14.58		
System I	\$13.11	\$1.47	9.9
System II	\$12.31	\$2.27	15.5

¹Weighted average of Units 1 and 4 computed from Part I by converting from BDU to BDT.

EQUIPMENT

ROLLER-BUNCHER

TRUCKS

GRIPPER

WANS

TRADER

WANS

(19.5 hr)

(73.0 hr)

(73.0 hr)

(63.5 hr)

(63.5 hr)

50

100

150

174.2

HOURS

0

Summary and Conclusions

The costs of harvesting merchantable material using conventional harvesting and near complete harvesting were almost the same: \$33.27/Mfbm and \$33.50/Mfbm, respectively. The cost of harvesting the nonmerchantable material indicates that a net profit *per acre* in a near complete harvest may be possible if markets develop for the residue.

It has been shown in Part II that a significant cost savings is possible in a carefully scheduled operation using the most productive equipment.

Further savings would be possible after the crews have had more experience with this method of logging.

In conclusion, more complete utilization of the fiber resource may be possible in the future by using near complete harvesting methods and carefully planned harvesting operations.

Appendix

General Specifications

Feller-Buncher - Drott Model 40 LC

Width	11'
Height	11' 8"
Weight	11,960 lb
Prime power	GMC Diesel 4-71
Maximum reach (from C.G.)*	25'
Maximum tree size (softwoods)	24"
Continuous rotating platform	180°

Chipharvester - Morbark Model SL 22

Width	8' 10"
Height	15' 4"
Weight (approx.)	32,000 lb
Prime power	GMC Diesel 8V 71
Feed rate	120 lin. ft/min
Maximum tree size	22"

Grapple Skidder - Timberjack Model 230D

Width	8' 1"
Height	7' 11"
Weight	12,740 lb
Power	GMC Diesel 6V 71
Tires (standard)	18.4 X 34
Speed range	2.22 - 17.64 mi/h
Grapple opening	8' 6.5"
Maximum horizontal reach	8' 5"

* C.G. = Center of gravity

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1973. Logging equipment, methods, and cost for near complete harvesting of lodgepole pine in Wyoming. USDA For. Serv. Res. Pap. INT-117, 15 p., illus. Intermountain Forest & Range Experiment Station, Ogden, Utah 84401.

Lodgepole pine (*Pinus contorta* Dougl.) in Wyoming was logged to near complete standards using a feller-buncher, grapple and choker rubber-tired skidders, and a portable chipper. Cost of removing the commercial timber was comparable to costs incurred in conventional harvesting. Cost of removing the logging residue and chipping it on the site shows promise for future utilization. A more efficient logging system is simulated and proposed for reducing the costs of near complete harvesting in the future.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

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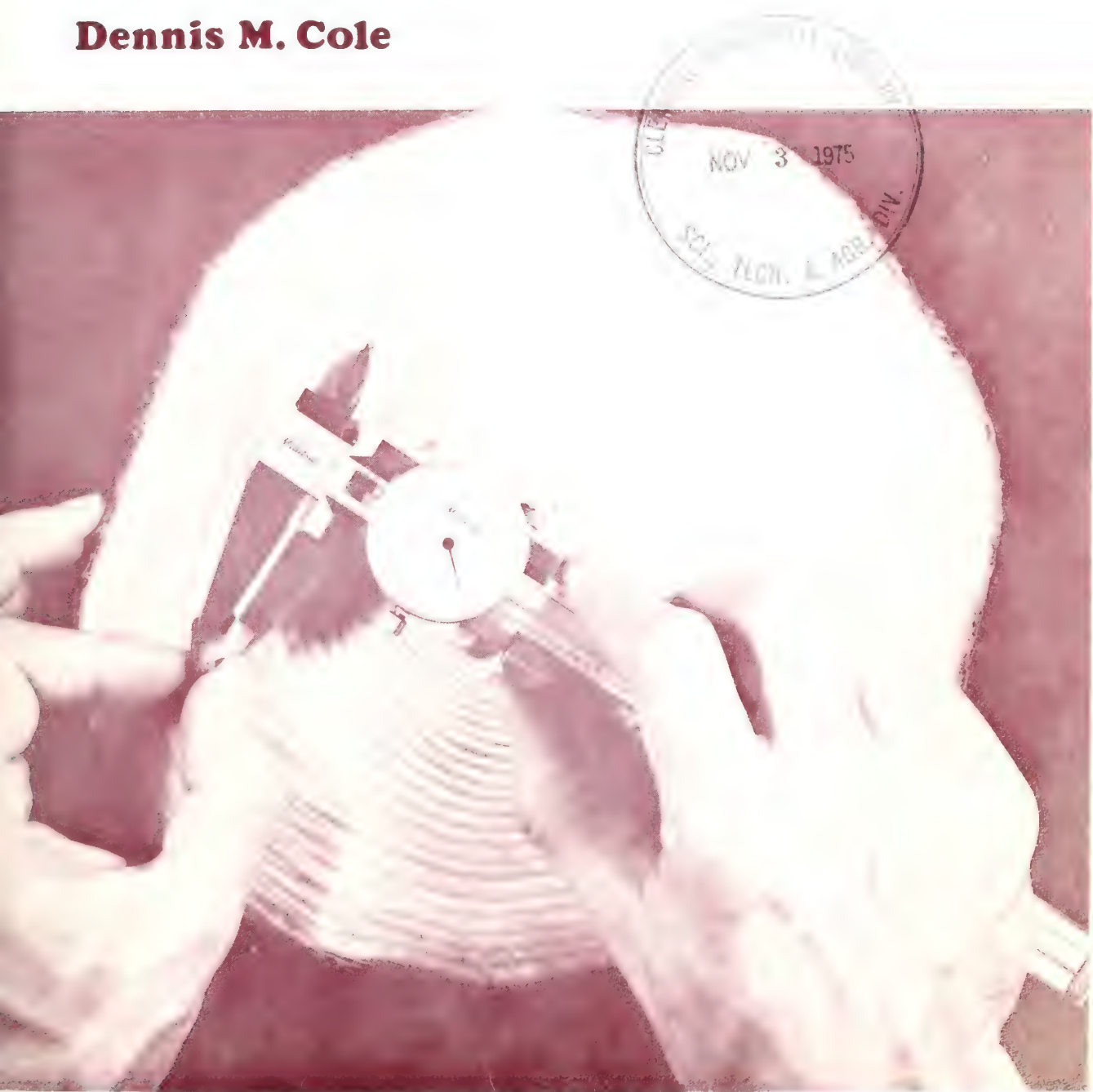
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Estimation of Phloem Thickness in Lodgepole Pine

Dennis M. Cole



USDA Forest Service Research Paper INT-148, 1973
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EXPERIMENT STATION
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THE AUTHOR

DENNIS M. COLE is an Associate Research Silviculturist working on research in the silviculture of lodgepole pine, stationed at Bozeman, Montana. His studies have been primarily concerned with the description and management of growth and yield relationships of lodgepole pine forests.

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Robert W. Harris, Director

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ABSTRACT

Analysis of data from 288 trees shows that phloem thickness of lodgepole pines is strongly related to tree growth expressions that reflect past tree vigor, such as periodic basal area increment, and d.b.h. and tree height in conjunction with tree age. Broad habitat-type groupings also significantly influence phloem thickness. Equations presented for estimating phloem thickness of individual trees are usable in construction of phloem thickness distributions for lodgepole pine stands. Such distributions can aid in developing risk classifications for assessing vulnerability of lodgepole pine stands to mountain pine beetle attack.

INTRODUCTION

In tree growth investigation, phloem thickness has been little studied until recently. Researchers and resource managers concerned with forests of lodgepole pine (*Pinus contorta* Mill.) are interested in the relationship between phloem thickness and mountain pine beetle (*Dendroctonus ponderosae* Hopk.).

The mountain pine beetle shows a strong preference for large-diameter trees in lodgepole pine stands (Hopping and Beall 1948, Cole and Amman 1969). Recent evidence indicates that brood survival of the beetles is related to thickness of phloem, the beetles being generally unable to produce a successful brood in trees with phloem thickness of less than about 0.12 inch (Roe and Amman 1970). Therefore, understanding tree diameter and phloem thickness distributions in lodgepole pine stands of various descriptions would be valuable. Considerable information in the form of stand table data is available for assessing diameter distributions in lodgepole pine stands, but there is virtually none that will allow estimation of phloem thickness in the same varying descriptions.

A method of modeling phloem thickness distributions for lodgepole pine stands under various management assumptions would be valuable because it could lead to the development of a risk classification for assessing stand vulnerability to the beetle. The starting point is the development of equations for estimating phloem thickness in lodgepole pine trees. This paper presents such equations and discusses the functional relationships underlying them.

METHODS

Data were collected and analyzed under a random sampling design using stratification by habitat types to assess basic site quality differences.

Observations

The study covered 288 trees in even-aged, unmanaged lodgepole pine stands at elevations ranging from 3,300 to 7,900 feet in western Montana and southeastern Idaho. Measured trees ranged in age from 11 to 155 years; in d.b.h. from 0.8 to 19.5 inches; and, in height from 8 to 103 feet. Data were obtained during remeasurement of permanent plots established for a stand density study and from temporary plots established to widen the range of tree sizes sampled for the phloem study. To minimize experimental error arising from measurement of incomplete phloem growth, the bulk of the sampling was done in the late summer and early fall. The distribution of data and the variation in phloem thickness, in relation to tree diameter, is illustrated in figure 1.

The basic measurements and observational data taken were suggested by literature review and correlation analysis of preliminary data. To provide the necessary growth measurements (in addition to measurements of tree, stand, and site attributes), phloem samples and increment cores were taken from the observation trees as described below.

Average phloem thickness.--Thickness to 0.01 inch was determined at breast height from measurement of excised samples, 5/8-inch square. In the permanent plot remeasurements, average phloem thickness was determined from two samples per tree, each located at 180° to the other on the axis of the average d.b.h. of the tree. Variance analysis of the thickness data indicated that error might be reduced by increasing the intensity of sampling for this attribute; therefore, with the supplemental data collected on the temporary plots, two additional phloem samples were excised from each tree. These were located 180° to each other but at right angles to the two measurements indexed on the average d.b.h. of the tree. Analysis of the data revealed no significant difference between the groups.

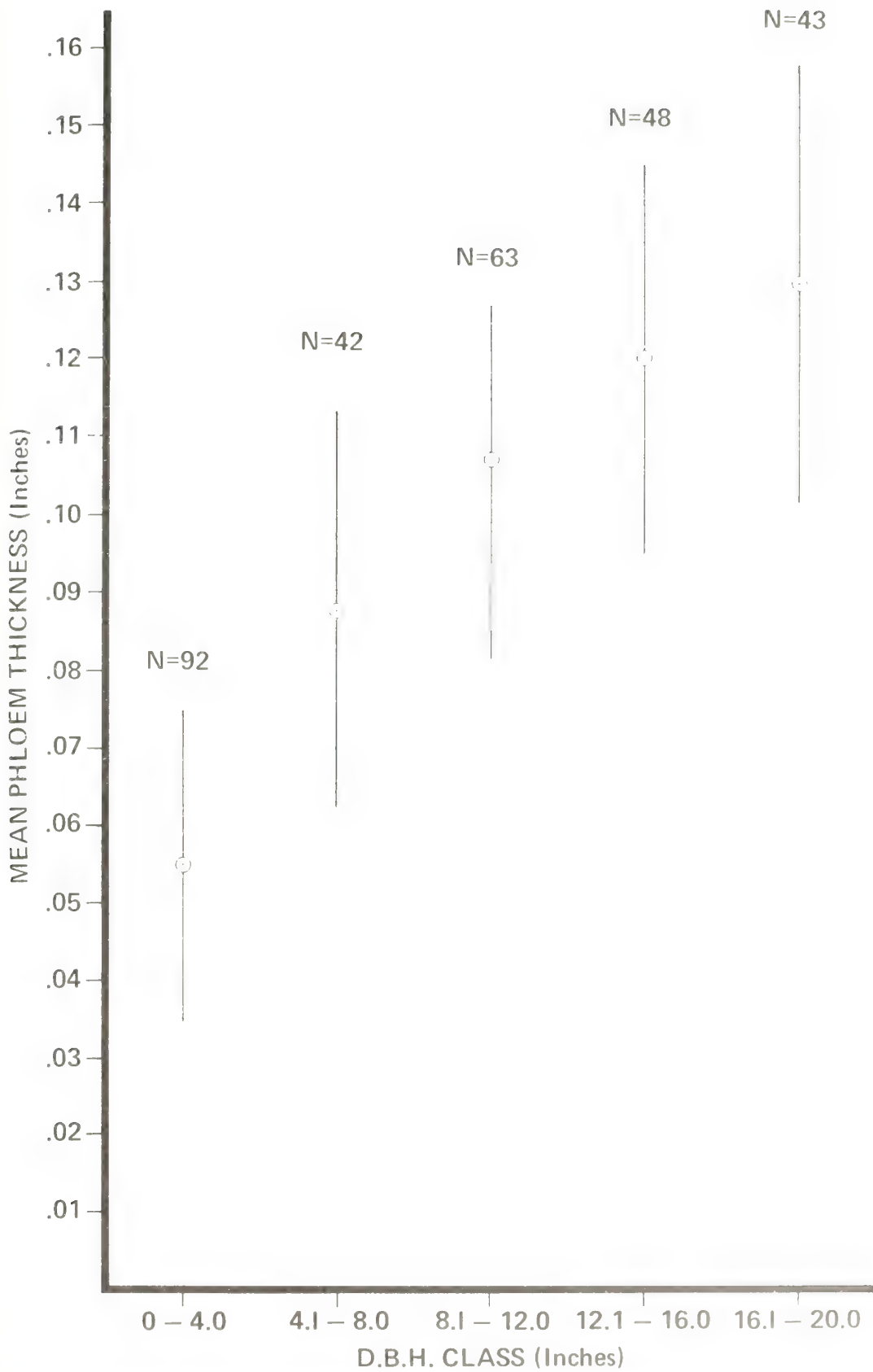


Figure 1.—Relationship of size, diameter, and age of *Pinus strobus* to phloem thickness.

Total "crevice" bark thickness.--This measurement (after Amman 1969) gives average total bark thickness, disregarding the highly variable ridges and corky tissue of older outer bark, which adds considerable variation to measurements. Measurements to the nearest 0.01 inch were taken from the excised samples used for phloem thickness determination.

Diameter at breast height, outside bark.--This was measured to the nearest 0.1 inch with a steel diameter tape.

Total tree height and crown length.--Both were measured at taped distances with a clinometer and recorded to the nearest foot.

Tree age at breast height; average 5- and 10-year radial growth.--Age and growth measurements to 0.01 inch were obtained from increment cores taken in coincident orientation with the phloem samples from each tree.

Tree-centered stand density.--This was determined as the average of two BAF 5 prism counts, each centered 15 feet from the center of the subject tree, in opposite directions and on the axis of the average diameter of the tree. The d.b.h. of each tree tallied was also recorded.

Elevation.--Elevation above mean sea level was determined to the nearest 50 feet, from topographical maps or by altimeter.

Crown class.--This was classified as dominant, codominant, intermediate, or suppressed, according to standard definitions (Society of American Foresters 1958).

Habitat types.--Types were identified according to the classification of Daubenmire and Daubenmire (1968). The habitat types in this study were only tentatively identified because they are outside the geographical area covered by the original classification. Nevertheless, broad agreement with the specified habitat types should at least establish whether or not phloem thickness variation is related to habitat types.

From the above measurements and observations, a set of independent variables was developed for use in regression analysis.

Analysis

From the observations taken, 19 individual tree, stand, or site attributes were determined to be independent variables for the gross analysis: habitat type, elevation, crown class, site index, crevice bark thickness, d.b.h., tree height, crown ratio, crown length, age, radial growth, average stand diameter, stand basal area, number of trees per acre, basal area percentile of subject tree,¹ crown competition factor (CCF) (Krajicek and others 1961; Alexander and others 1967), average sum of diameters of prism tally, average sum of diameters squared of prism tally, and average prism count.

The five habitat types considered in the analysis were found to be significantly related to phloem thickness at the 1 percent level of probability. Tests between the individual habitat types, however, according to Students' *t* distribution, indicated that

¹This is the proportion of basal area represented by all trees in diameter classes up to and including the diameter class of the subject tree-expressed as a percentage of the total stand basal area.

For these data the habitat types should be statistically considered as two groups. A dummy variable was therefore used, with $X_0 = 1$ for all observations, and the variable X_1 being used for habitat-type group identification as follows:

X_0	X_1		
1	1	=	Group 1
1	1	=	
1	0	=	Group 2
1	0	=	
1	0	=	

The various other independent variables were designated X_2 through X_n .

Expressions of the form $Y = b_0X_0 + b_1X_1 + b_2X_2 + \dots + b_nX_n$ were fitted to the data using the REX computer program of Grosenbaugh (1967) in which:

Y = phloem thickness in inches, or transforms thereof

X_i = the individual independent variables, including various interaction terms

$i = 0$ to n .

Fitted regressions were subjected to a full combinatorial screening analysis, in which all combinations of independent variables were compared for their performance in accounting for variation in phloem thickness. Selected residual plottings were made to assay for data trends.

Initial screenings quickly reduced the number of variables showing promise in prediction of phloem thickness. Of the 19 independent variables, only the following were retained for further investigation: (1) habitat-type group, (2) elevation, (3) d.b.h., (4) tree height, (5) crown ratio, (6) crown length, (7) age, (8) radial growth, and (9) average prism count.

Interaction and power terms of the nine retained independent variables were tested, but none added to or furnished improvement over their basic variable form. Selected residual plottings were made to assay for nonhomogeneous variance and to point out inadequacy of the model. A small amount of nonhomogeneous variance was indicated when phloem thickness (the dependent variable Y) was expressed in inches. A logarithmic transformation of Y was found to compensate, and as its Index of Fit (Turnival 1961) was virtually the same (0.024 vs. 0.022 for Y untransformed), the logarithmic transformation became the preferred form. Plotting of residuals over the individual independent variables did, however, suggest that lateral growth in square inches (basal area increment), as well as radial growth in inches should be included in the analysis, and that the logarithmic transformations of d.b.h., height, crown length, and basal area increment should be used.

From these analyses, a number of equations that are satisfactory for the prediction of phloem thickness under different stand conditions were developed.

RESULTS AND DISCUSSION

Phloem thickness of lodgepole pine trees can be described by a number of inter-related variables, some of which are more readily measured than others. As an example, in this analysis (as expected) crevice bark thickness was found to be highly correlated with phloem thickness (the coefficient of determination, $r^2 = 0.67$). It was not seriously considered, however, as a useful variable in equations intended for modeling stand phloem distributions, because efforts to measure it can better be spent in measuring phloem thickness directly. The other variables eliminated were all dropped because they failed to contribute sufficiently to the explanation of phloem variation. Some of these might also have been dropped on the basis of practicality, however.

Relation of Phloem Thickness to the Regression Variables

In the multiple regression analysis, a maximum of 73.5 percent of the variance in observed phloem thickness was accounted for by the following six basic variables: habitat-type group, HT; 5-year basal area increment (BAI), G; d.b.h., d; tree height, h; elevation, El; and age at breast height, A, as shown in regression 1, table 1. Of these the logarithm of BAI alone (regression 11) accounted for 64 percent of phloem variance. Here, BAI over the most recent 5-year growth period is probably functioning as an indicator of current tree vigor; as such, it can be expected to reflect various tree growth expressions, including phloem thickness.

Habitat-type group was the next most important variable, occurring in all the higher ranking regressions of from two to six independent variables. In the presence of all other final variables, it accounted for an additional 2.8 percent of the total phloem thickness variance--or 9.6 percent of the remaining variance otherwise left unexplained. Nevertheless, because the present identification of types for the study area is uncertain, habitat type was not considered strongly as a usable variable for developing phloem prediction equations.

The relative contribution of the other variables is shown by the differences in percentages of variance accounted for with successive elimination of variables (table 1). Thus, the elimination of age is seen to reduce the percentage only 0.5 point (regression 2); subsequent elimination of elevation, 0.7 point (regression 3); tree height, 1.1 points (regression 4); and d.b.h., 2.1 points (regression 9). The contribution of the other five variables is small when compared to the performance of BAI, but each is statistically significant at the 1 percent level of probability.

Of the six final independent variables, only habitat type and elevation are not individual tree attributes. All, however, are recognized as being either influences on tree vigor (habitat type, elevation, and age) or indirect indicators of vigor (BAI, d.b.h., and height). Because annual xylem and phloem growth are the complementary sum of annual lateral cambial growth, it is not surprising that 5-year basal area increment

Table 1.--Multiple regression relationships between growth and environmental variables

Regression No.	Basic variables	Percentage of variance accounted for
1	HT,G,d,h,E1,A	73.5
2	HT,G,d,h,E1	73.0
3	HT,G,d,h	72.3
4	HT,G,d	70.4
5	HT,d,E1,h,A	72.1
6	HT,d,E1,A	70.8
7	HT,d,E1	61.7
8	HT,G,E1	69.3
9	HT,G	68.3
10	G,E1	67.1
11	G	64.0

¹ For regression 1, the complete multivariable relationship, the equation is:

$$Y = b_0 + b_1HT + b_2\ln G + b_3\ln d + b_4h + b_5E1 + b_6A,$$

where Y is the natural logarithm (ln) of phloem thickness at breast height in inches; HT = habitat-type group; G = last 5 years of basal area increment in square inches (BAI); d = d.b.h., outside bark, in inches; h = total tree height in feet; E1 = elevation above sea level in hundreds of feet; and A = tree age at breast height in years. The other regressions use the same forms of the variables, differing only in the combinations of the variables as indicated.

(the most *contemporary* of the growth expressions considered as independent variables) is so strongly related to phloem thickness. The variables, tree height and d.b.h., are similarly regarded as *cumulative* expressions of relative tree vigor.

When used with d.b.h. and height, tree age--aside from its own implications as a vigor factor--seems to serve as an indirect indicator of average growth rate that is nearly as effective in explaining phloem thickness variance as BAI. This can be seen in comparisons of regressions 1, 5, 6, and 7 of table 1. Regression 5 shows that elimination of BAI from the variables of regression 1 results in a decrease in explained variance of only 1.4 percent, whereas elimination of height further reduces the value 1.3 points (regression 5 vs. regression 6). Elimination of age from regression 6, however, results in a drop of 9.1 points--to 61.7 percent (regression 7).

The contribution of elevation, though statistically significant at the 1 percent level, is relatively small. It seems to have greater effect when habitat type is not included in the regression. Compare the difference in explained variance of regressions 8 and 9, containing HT, with that of regressions 10 and 11, not containing HT. It appears that habitat types indirectly account for much of the elevation effect on phloem thickness variation--a not unexpected finding, since elevation is often an element in the delineation of habitat types.

The relationship of elevation to phloem thickness was also influenced by an inadvertently forced positive correlation ($r^2 = 0.20$) between elevation and d.b.h. in the temporary plot data. The requirement that annual phloem growth be essentially finished before sampling could begin limited our ability to find strictly comparable diameter distributions for each of the different habitat types. As a result, habitat types sampled at higher elevations tended, by chance, to have older, larger diameter trees. The elevation-phloem thickness relationship was thus inflated from an r^2 value of 0.03 in the permanent plot data to a value of 0.09 in the combined data of this report. The elevation relationships reported here, then, can only be viewed as general indicators of the probable nature of multiple correlations involving elevation.

Neither site index nor the various measures of stand density and local competition used in this study were found to contribute much to phloem thickness estimation. Previous experience (Arthur L. Roe 1970, personal communication) has suggested that habitat types are more likely than site index to indicate basic site quality for a number of lodgepole pine growth expressions. In addition, effects of site quality on phloem thickness are probably represented indirectly by such growth expressions as basal area increment, d.b.h., and height. The relatively limited usefulness of stand density and relative competition measures as indicators was not expected, however. These effects also appear to have been effectively represented by the growth rate expressions included in the model.

Phloem thickness prediction coefficients for habitat-type groupings are not used in the equations because the limited sampling of this study, together with the uncertainties of the habitat-type identification, does not warrant quantification of the relationship. Extension of the habitat-type classification (in progress), followed by intensive sampling of stand conditions, can be expected to make prediction from habitat type reliable. Meanwhile, estimations of the distribution of average phloem thickness within stands of various descriptions can be obtained with the prediction equations for individual trees presented in the next section.

Estimating Phloem Thickness

A selected number of the relationships of table 1 (minus habitat-type groupings and elevation) were fitted to the data to generate coefficients that would provide prediction equations usable under a variety of stand conditions. These are listed in table 2.

When all data are available, either equation 1 or 2 would probably be preferred for estimation of phloem thickness of individual trees, particularly in computer simulation applications based on stand growth prognosis by the individual tree approach. When basal area increment is not available, however, or when application to stand tables or stand table projections is indicated, other equations may become more practical. The standard errors of estimates are presented in terms of percentages of the mean to allow direct comparison of the equations in original units of phloem measurement (inches).

Uses of the equations should be restricted to the ranges of the independent variables specified under "Observations" on page 2. Extrapolation should be made with caution. The equations should be regarded only as interim estimators for lodgepole pine outside the area of western Montana and southeastern Idaho.

Conclusions

From the results of this study, we can conclude that:

1. Phloem thickness of lodgepole pine trees is significantly influenced by habitat type. Although significant differences were detectable for only two broad habitat-type groups, more intensive sampling within habitat types might well yield separate estimating equations for many of the types.
2. Phloem thickness of lodgepole pines is functionally related to tree vigor, as shown by the high degrees of positive correlation between phloem thickness and the several growth expressions considered.

Consequently, cultural treatments that result in accelerated growth of the residual stand can be expected also to result in increased phloem thickness for any given age or diameter class. The effect cannot be precisely quantified for sensitive management use until more intensive sampling of habitat types and stand conditions has been done.

Table 2.---Logarithmic regression equations, r^2 , and r for the following

Equation No.	Basic variables	Equations	Percentage of variance accounted for	Standard error of estimate	r^2 of mean
1	G,d,h,A	$Y = -5.14859 + 0.14278 \ln(G) + 0.17283 \ln(d)$ $- 0.00858 h + 0.00115 A$	69.4	27.6	
2	G,d,h	$Y = -5.17152 + 0.12591 \ln(G) + 0.50952 \ln(d)$ $- 0.0077 h$	69.3	27.7	
3	d,h,A	$Y = -5.40418 + 0.85547 \ln(d) - 0.01151 h$ $- 0.00105 A$	67.1	28.8	
4	d,h	$Y = -5.41275 + 0.866 \ln(d) - 0.015 h$	66.9	28.8	
5	d,A	$Y = -5.5845 + 0.65145 \ln(d) - .00452 A$	65.2	30.6	

Y = natural logarithm of pilose thickness at preart height, in inches.

G = first 5 years of basal area increment in square inches; d = diameter outside bark, in inches; h = total tree height in feet; A = tree age at breast height in years.

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Analysis of data from 255 trees shows that phloem thickness of lodgepole pines is strongly related to tree growth expressions that reflect past tree vigor, such as periodic basal area increment, and d.b.h. and tree height in conjunction with tree age. Broad habitat-type groupings also significantly influence phloem thickness. Equations presented for estimating phloem thickness of individual trees are available in construction of phloem thickness distributions for lodgepole pine stands. Such distributions can aid in developing risk classifications for assessing vulnerability of lodgepole pine stands to mountain pine beetle attack. (OFFORD: 523.1. KEYWORDS: bark thickness, phloem thickness, lodgepole pine, mountain pine beetle.

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FAILURE CONDITIONS IN INFINITE SLOPES AND THE RESULTING SOIL PRESSURES

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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U. S. Department of Agriculture
Ogden, Utah 84401
Robert W. Harris, Director

THE AUTHORS

WILLIAM S. HARTSOG is a Research Engineer, Forest Engineering Research, stationed at the Forestry Sciences Laboratory in Bozeman, Montana. He has been involved with slope stability problems on various assignments over the past 6 years.

GLEN L. MARTIN is Professor and Head of the Department of Civil Engineering and Engineering Mechanics, Montana State University. He has worked 15 years as a consultant, teacher, and researcher in the field of Soil Mechanics and Slope Stability Analysis.

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ABSTRACT

The Rankine assumptions were used as a basis for developing equations for calculating active and passive earth pressures within a slope extending to infinity. The analysis considers: cohesive and noncohesive soils, the angle of internal friction of the soil, seepage forces caused by a ground water table that is parallel to the ground surface, and the plane on which the stresses are to be found may be at any inclination.

INTRODUCTION

Beginning with Rankine more than a century ago, scientists and engineers alike have sought to improve techniques for calculating soil pressures beneath the earth's surface. This capability has been important not only for predicting soil pressures against structures such as retaining walls and foundations, but also for predicting the depths and pressures at which soil masses will fail when disturbed by either man or nature.

This paper, based on Rankine's classic assumptions and the contributions of others, offers some additional refinements for calculating soil pressures. The equations have particular relevance to much of the steep, mountainous lands managed by the USDA Forest Service, particularly the Idaho Batholith, where Intermountain Station engineers and scientists are studying slope stability and erosion problems.

In 1860, Rankine presented the original theory for calculating lateral earth pressures within a slope of infinite extent. Rankine's development was based on a conjugate stress relationship between vertical stresses and stresses on a vertical plane and considered a dry cohesionless material with either a sloping or a horizontal surface. During the latter part of the nineteenth century, the Mohr circle of stresses was presented for the graphic representation of the state of stress. The analytical work of Rankine was subsequently adapted to a graphical method using the Mohr circle of stresses.

In 1915, Bell extended Rankine's work to include cohesive soils. Bell's graphical procedure made use of Mohr's stress circle, but in an inconvenient manner. Martin (1961) derived an analytical expression that extends Rankine's work to include cohesive soils, but it includes neither seepage conditions nor a variable plan of investigation.

This paper extends Martin's analytical development to include stresses on any plane in the slope, and includes seepage stresses in the analysis. It is assumed in the following development that seepage stresses are caused by a water table parallel to the ground surface. A chronological summary of the developments based on Rankine's assumptions is shown in table 1.

The graphical methods presently being used to determine earth pressures are tedious and time consuming to use because, unlike the analytical expressions developed herein, they cannot be processed by computer.

Table 1.--Chronological summary of the development of infinite slope earth pressures

Investigator	Factors Considered					Approach	
	Angle of slope	Angle of internal friction	Unit cohesion of the soil	Angle of the plane of investigation	Seepage	Graphical	Analytical
Rankine	X	X		vertical			X
Bell	X	X	X	vertical		X	
Martin	X	X	X	vertical			X
Hartsog	X	X	X	any	X		X

STRESS RELATIONSHIPS ON A PLANE PARALLEL TO THE GROUND SURFACE WITHIN AN INFINITE SLOPE

The term, infinite slope, is defined as a slope of constant inclination of unlimited extent. For practical purposes, a slope that has a length to depth ratio of 20:1 or greater has been considered an infinite slope.

The classical infinite slope analysis requires that soil properties be constant at any and all vertical sections along the slope. If this requirement is met, the slope can be studied by analyzing the stress conditions within an elemental volume of soil.

Figure 1 shows the basic assumed geometry of the infinite slope. In figure 1, Z is the depth to the plane of investigation, Z_w is the depth to the water table, and $(Z-Z_w)$ is the vertical distance from the water table to the plane of investigation. The total unit weight of the soil material above the water table is denoted as γ_t , and γ_{sat} is the saturated unit weight of the soil. The angle the ground surface makes with the horizontal is denoted as θ . It is assumed that the planes representing the ground surface and the water table are parallel.

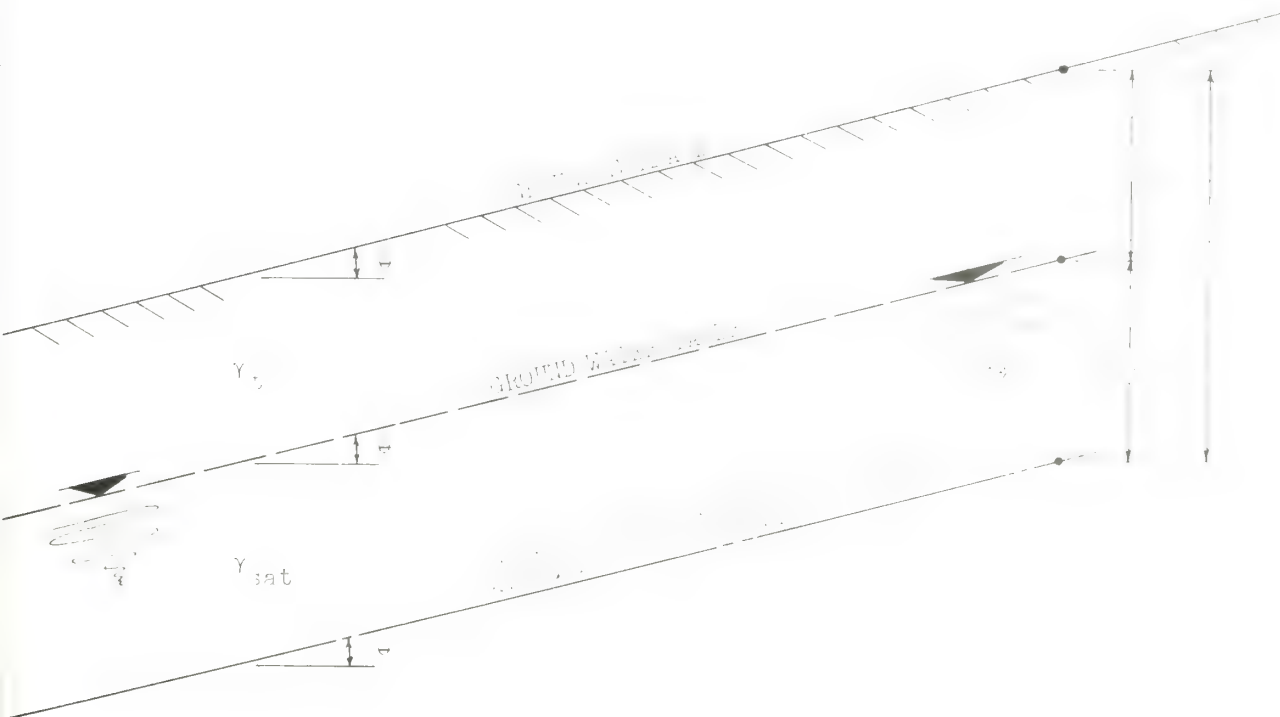


Figure 1.--Profile of an infinite slope.

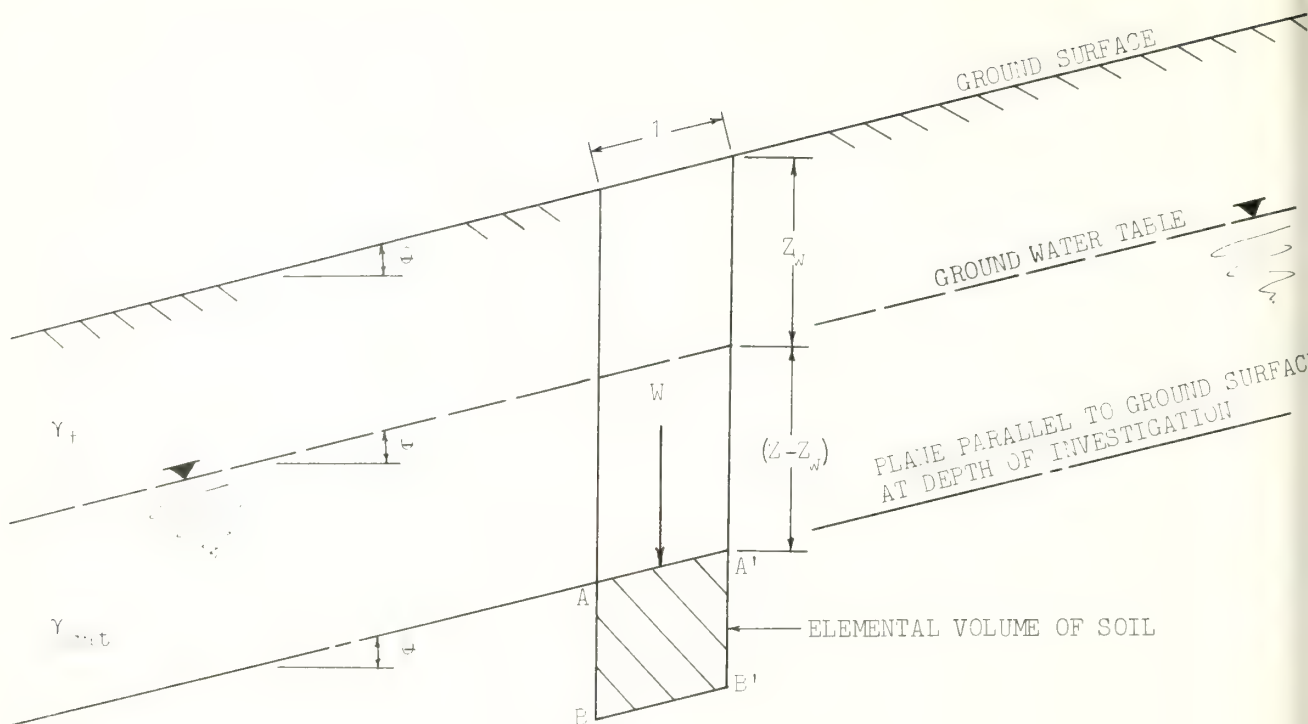


Figure 2.--An elemental volume of soil, AA'BB', within an infinite slope.

The slope profile with an elemental volume of soil (AA'BB') is shown in figure 2. If a unit dimension is assumed normal to the plane of figure 2, and if AA' is assumed to be of unit length, the resulting plane (which shall be referred to as plane A-A') will be of unit area. The force, W, acting on plane A-A', is equal to the weight of the vertical column of soil above plane A-A'.

The equation for the vertical force, W, is found by adding the products of respective unit weights and volumes within the vertical column of soil:

$$W = \gamma_t Z_w \cos \theta + \gamma_{sat} (Z - Z_w) \cos \theta. \quad (1)$$

Equation 1 is valid for the general case; that is, plane A-A' is below the ground water table. When plane A-A' is above the ground water table, the quantity $(Z - Z_w)$ is zero and Z_w is replaced with Z.

The vertical force, W, can be resolved into components normal (N) and tangential (T) to plane A-A', as shown in figure 3. The expressions for the normal force and the tangential force are, therefore:

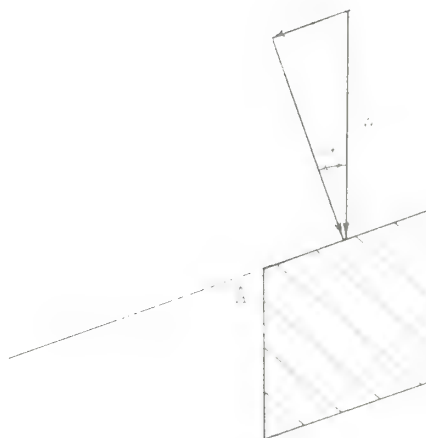
$$N = \gamma_t Z_w \cos^2 \theta + \gamma_{sat} (Z - Z_w) \cos^2 \theta, \quad (2)$$

$$T = \gamma_t Z_w \sin \theta \cos \theta + \gamma_{sat} (Z - Z_w) \sin \theta \cos \theta. \quad (3)$$

The normal stress, σ_a , shown in figure 4, is equal in magnitude to the force N, because plane A-A' is of unit area. It follows, from equation 2, that:

$$\sigma_a = \gamma_t Z_w \cos^2 \theta + \gamma_{sat} (Z - Z_w) \cos^2 \theta. \quad (4)$$

Figure 3.--Force components acting on plane A-A'.



Similarly, the tangential stress, τ_a , is equal in magnitude to the force T . From equation 3, the equation for τ_a can be written as:

$$\tau_a = \gamma_t Z_w \sin \theta \cos \theta + \gamma_{sat} (Z - Z_w) \sin \theta \cos \theta. \quad (5)$$

Because the analysis will be on the basis of effective stresses, it is necessary to determine the neutral stress, u . The neutral stress is found by use of a flow net, as shown in figure 5. The pressure head along an equipotential line is equal to $(Z - Z_w) \cos^2 \theta$. The neutral stress on plane A-A' is the pressure head multiplied by the unit weight of water (γ_w):

$$u = \gamma_w (Z - Z_w) \cos^2 \theta. \quad (6)$$

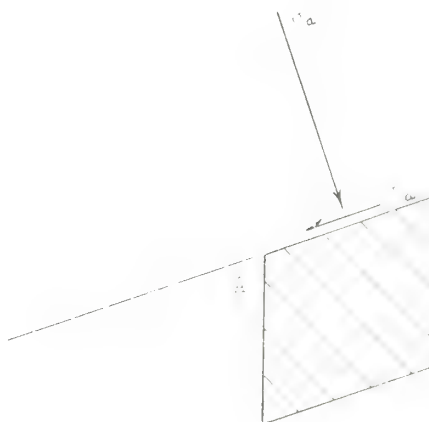
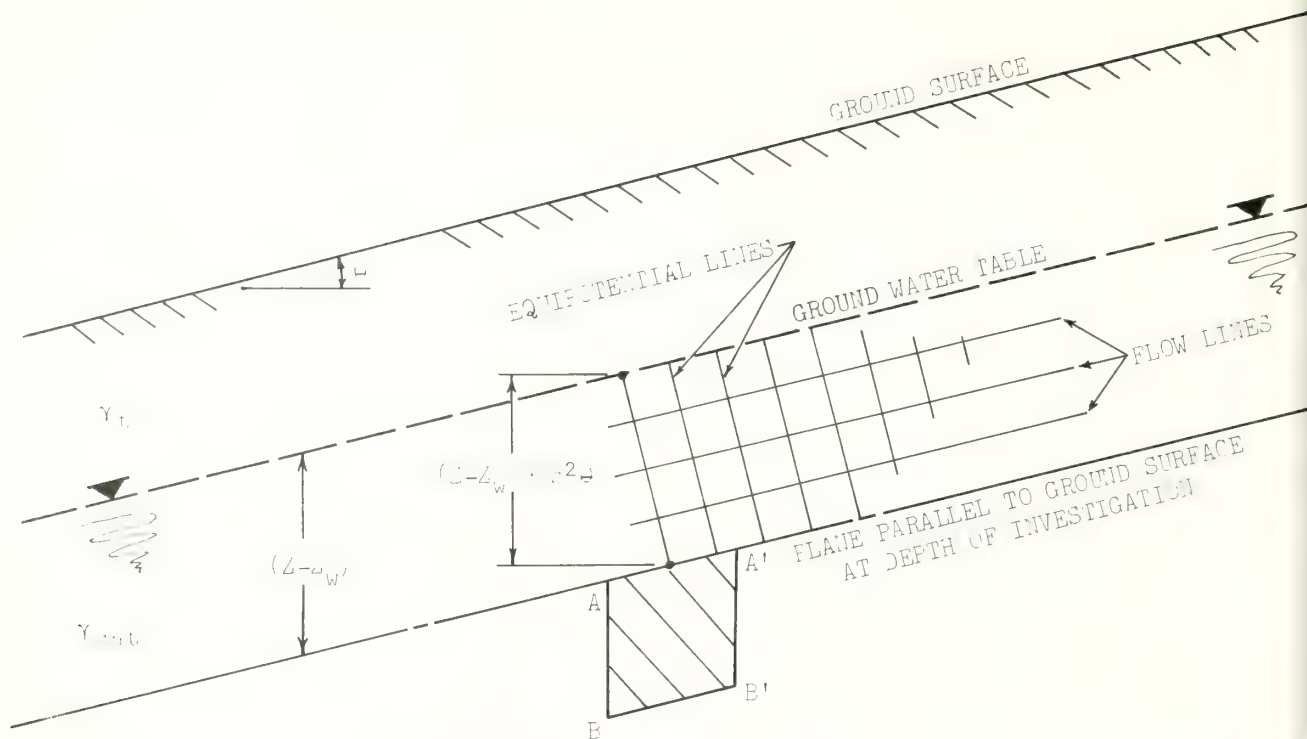


Figure 4.--Stresses acting on plane A-A'.



Note: hydraulic gradient $i = \sin\theta$

Figure 5.--Flow net within an infinite slope.

The effective stress, $\bar{\sigma}_a$, is found by subtracting the neutral stress from the total stress:

$$\bar{\sigma}_a = \gamma_t Z_w \cos^2\theta + \gamma_{sat} (Z - Z_w) \cos^2\theta - \gamma_w (Z - Z_w) \cos^2\theta. \quad (7)$$

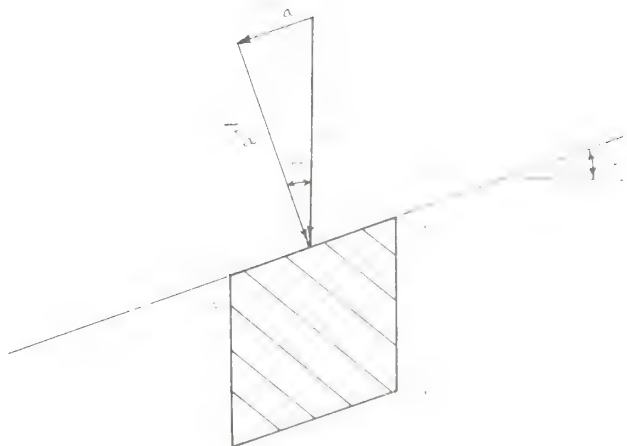
Because the buoyant unit weight, γ_b , is equal to $(\gamma_{sat} - \gamma_w)$, equation 7 can be written as:

$$\bar{\sigma}_a = \gamma_t Z_w \cos^2\theta + \gamma_b (Z - Z_w) \cos^2\theta. \quad (8)$$

Because water cannot resist shear stress at negligible velocities, the shear stress, τ_a , is not affected by the neutral stress. Equations 5 and 8 are the basic relationships for the effective stresses at a given depth and on a given plane of investigation. With this information, the stress condition $(\bar{\sigma}_a, \tau_a)$ may be adapted to a Mohr diagram.

Stresses cannot be added vectorially because they are not vector quantities, but because they are acting on the unit area of plane A-A', the normal and tangential stresses can be used interchangeably with normal and tangential forces. The subsequent development makes use of this resolving of stresses in order to define obliquity angles (the angle between the resultant and the normal effective stress).

Figure 6.--Stress relationships for plane A-A' above the water table.



There are three different conditions for which the obliquity angle can be defined:

Case I. Plane A-A' above the water table. When plane A-A' is above the water table the angle of obliquity is equal to the slope angle, θ , as shown in figure 6.

Case II. Plane A-A' below the water table with the water table coinciding with the ground surface. The obliquity angle, β , is defined in terms of effective stresses as shown in figure 7. The tangent of the obliquity angle is found by dividing the tangential stress by the effective normal stress:

$$\tan \beta = \frac{\gamma_{sat} (Z - Z_w) \sin \theta \cos \theta}{\gamma_b (Z - Z_w) \cos \theta} \quad (9)$$

Solving equation 9 for the angle of obliquity, β , yields:

$$\beta = \tan^{-1} \left[\left(1 + \frac{\gamma_w}{\gamma_b} \right) \tan \theta \right] \quad (10)$$

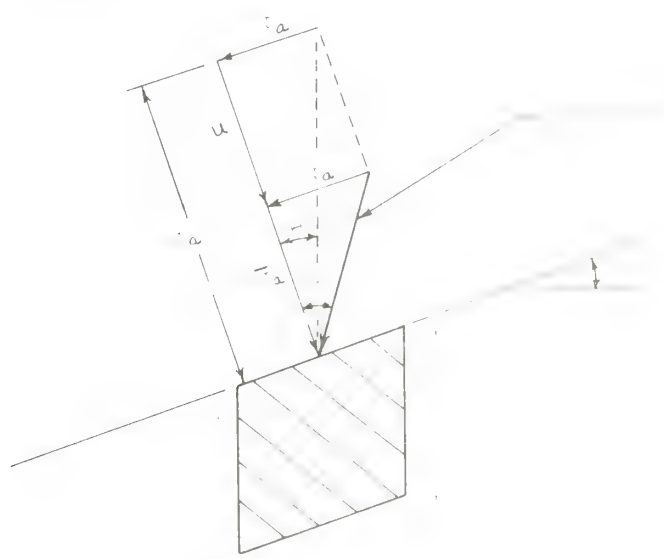


Figure 7.--Stress relationships for plane A-A' below the water table with the water table coinciding with the ground surface.

Case III. Plane A-A' below the water table with the water table below the ground surface. For this general case, shown in figure 8, the tangent of the obliquity angle, ψ , is the quotient of the tangential stress and the effective normal stress:

$$\tan \psi = \frac{\gamma_t Z_w \sin \theta \cos \theta + \gamma_{sat} (Z - Z_w) \sin \theta \cos \theta}{\gamma_t Z_w \cos^2 \theta + \gamma_b (Z - Z_w) \cos^2 \theta} \quad (11)$$

Rewriting equation 11 and solving for the obliquity angle yields:

$$\psi = \tan^{-1} \left\{ \frac{\left[\gamma_t Z_w + \gamma_{sat} (Z - Z_w) \right]}{\left[\gamma_t Z_w + \gamma_b (Z - Z_w) \right]} \tan \theta \right\} \quad (12)$$

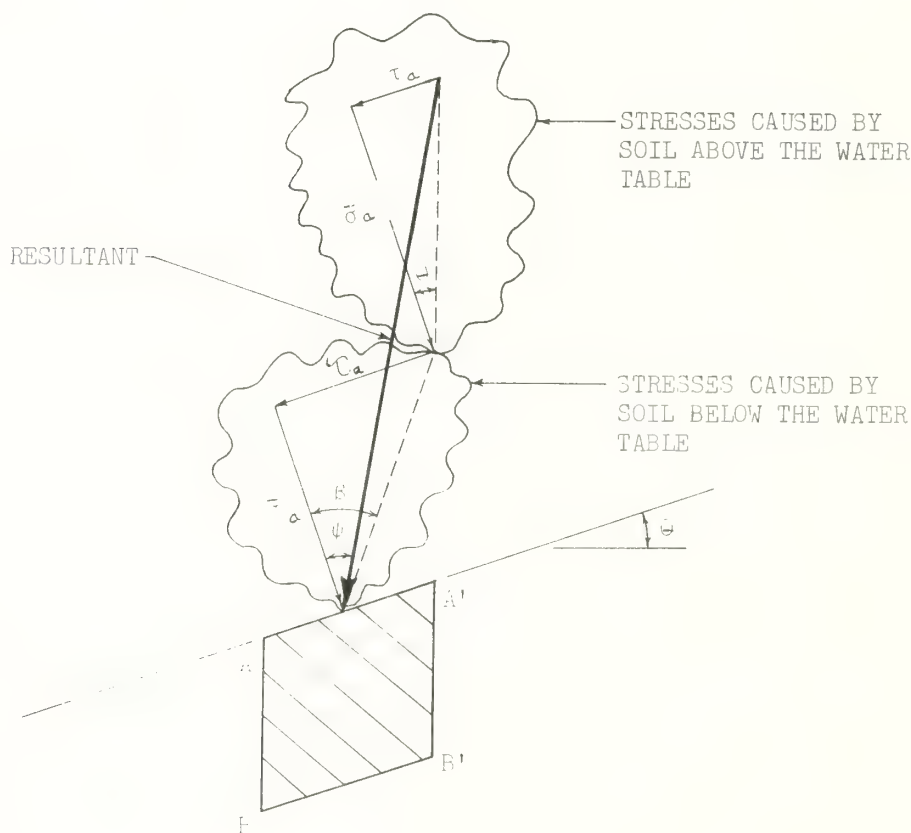


Figure 8.--Stress relationships for plane A-A' below the water table with the water table below the ground surface.

MOHR'S CIRCLE OF STRESSES

The Mohr circle of stresses is used to find the state of stress on any plane perpendicular to the plane of elemental volume of soil, AA'BB', shown in figure 2. Sign conventions used are those commonly used in soil mechanics; normal stresses in compression are positive and counterclockwise shear stresses are positive.

When the effective stresses, $\bar{\sigma}_a$ and τ_a , are plotted on Mohr's coordinates, the obliquities of the various components are as shown in figure 9. Note that the stress condition on plane A-A' is a function of depth. The state of stress ($\bar{\sigma}_a$, τ_a) will lie on line DE if plane A-A' is above the water table, or on line EF if plane A-A' is below the water table. The state of stress ($\bar{\sigma}_a$, τ_a) shown in figure 9 can be adapted to a Mohr diagram, as shown in figure 10.



Figure 9.--Stresses on plane A-A' shown on Mohr's coordinates.

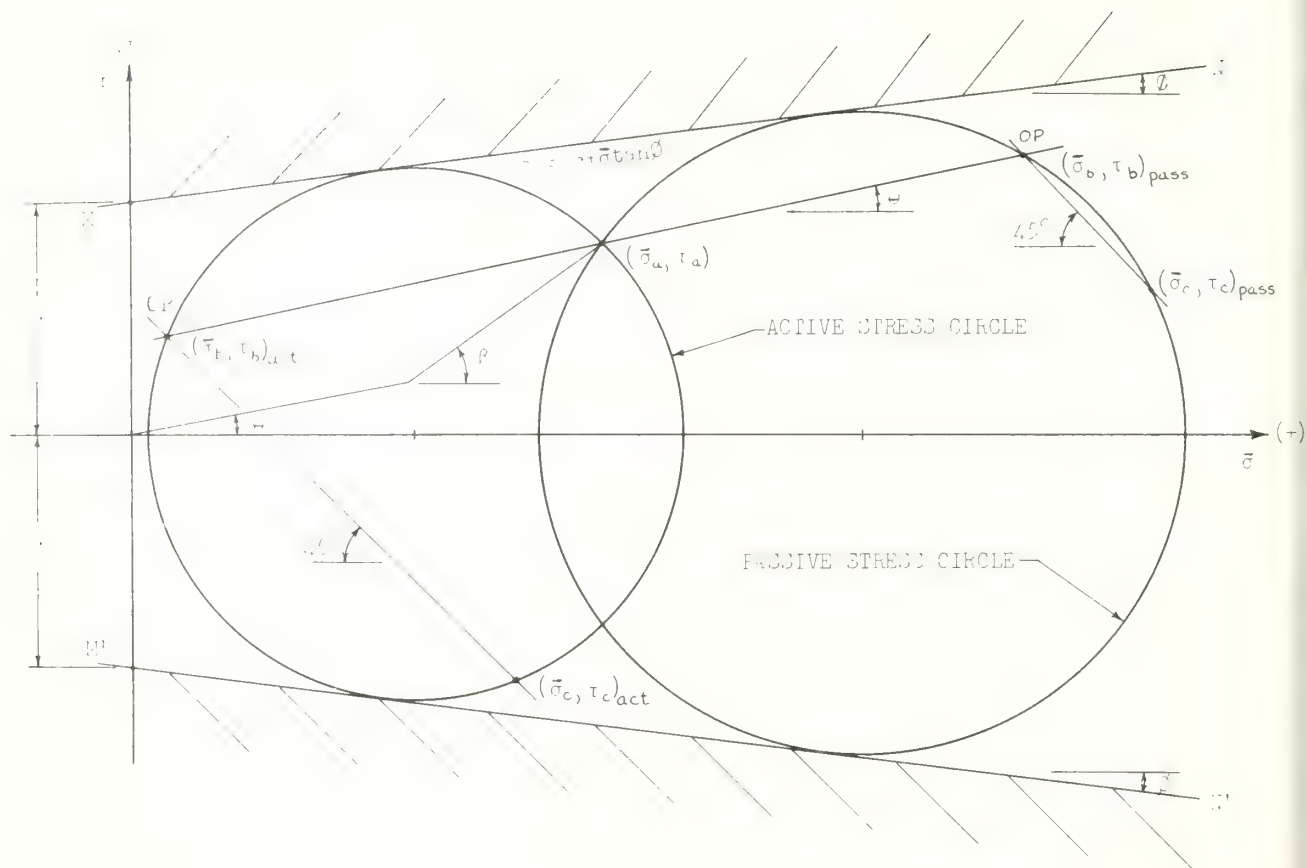


Figure 10.--Mohr diagram for active and passive stress conditions.

The strength characteristics of a soil material may be defined by Coulomb's equation:

$$s = c + \bar{\sigma} \tan \phi. \quad (13)$$

Where: s = the shear strength of the soil material;

c = the unit cohesion;

$\bar{\sigma}$ = the normal effective stress; and

ϕ = the angle of internal friction.

Equation 13 is shown graphically in figure 10, and this graphic illustration of equation 13 is known as the Mohr rupture envelope. The leaves of the Mohr rupture envelope, MN and M'N', shown in figure 10, represent the strength of the soil based on Coulomb's equation. A state of stress above MN or below M'N' will cause failure of the slope, whereas a state of stress that lies within the envelope may exist in a stable slope. The leaves of the envelope define impending failure conditions.

The main objective of this development is to find equations for two limiting values of stresses, commonly called the active and passive states of stress. When the soil is on verge of failure it will be in a state of plastic equilibrium.

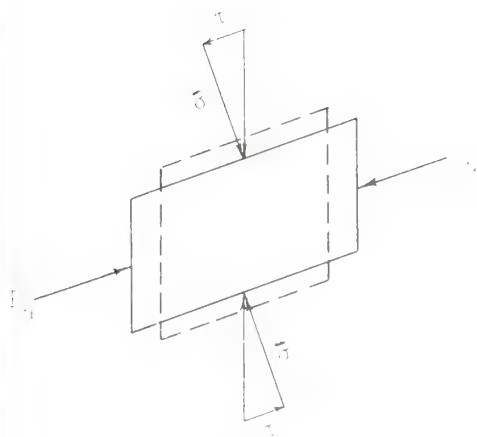


Figure 11.--Active state of stress.

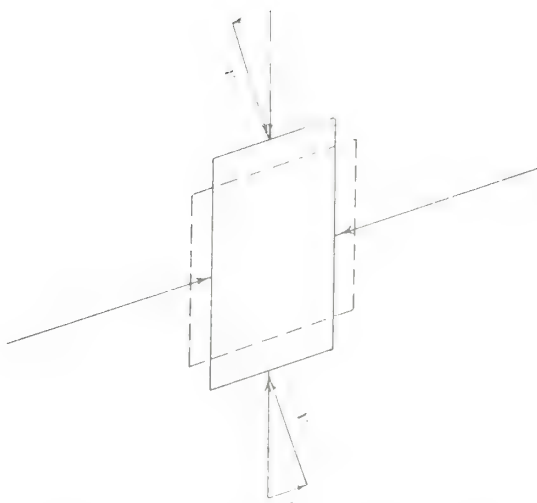


Figure 12.--Passive state of stress.

In the active case the lateral pressure is relieved and elongation occurs parallel to the direction of pressure release, as shown in figure 11. The lateral pressure, P_a , shown in figure 11, is the minimum which will maintain stability. This state of stress is shown by the active stress circle in figure 10.

In the passive case the lateral pressure is increased and compression occurs parallel to the direction of pressure increase, as shown in figure 12. The lateral pressure, P_p , shown in figure 12, is the maximum that will maintain stability. This state of stress is shown by the passive stress circle in figure 10.

Figure 10 shows that three conditions must be met for a soil to be in an active or passive state of stress: (1) The stress circle must be tangent to the Mohr failure envelope, (2) the center of the stress circle must lie on the $\bar{\sigma}$ axis, and (3) the stress circle must pass through the point of known stress $(\bar{\sigma}_a, \tau_a)$.

A modification of the Mohr's circle of stresses will be used herein. This modification, the origin of planes, allows a better visualization of the stresses and the orientation of planes on which the stresses act than the conventional Mohr's circle method. The origin of planes, OP, is shown in figure 10 and is obtained as follows:

1. Through the point of known stress condition, draw a line oriented identically to the plane on which the known stress acts.
2. The intersection of this line and the circle of stresses locate the origin of planes $(\bar{\sigma}_b, \tau_b)$.
3. The stress condition on any plane can be found by constructing a line oriented identically to the plane on which the stresses are to be found.
4. The point where this line again intersects the circle of stresses yields the desired stress condition $(\bar{\sigma}_c, \tau_c)$.

The stresses for the active case $(\bar{\sigma}_c, \tau_c)_{act}$ and the passive case $(\bar{\sigma}_c, \tau_c)_{pass}$ are shown for planes oriented 45° clockwise from the horizontal.

ANALYTICAL DEVELOPMENT

The problem is to develop expressions for the normal and tangential stresses for the active and passive states of stress, with the angle of the investigation, α , being one of the variables. Other variables in these expressions are: the known stress condition $(\bar{\sigma}_a, \tau_a)$; the slope inclination, θ ; and the strength characteristics of the soil, c and ϕ . There is no need to develop separate equations for $(\bar{\sigma}_c, \tau_c)_{act}$ and $(\bar{\sigma}_c, \tau_c)_{pass}$ because the development results in a quadratic equation that yields solutions for both the active and passive states of stress.

The equation for a line parallel to the ground surface and passing through point $(\bar{\sigma}_a, \tau_a)$, as shown in figure 13, is:

$$\tau = \bar{\sigma} \tan \theta + b, \quad (14)$$

where b is the intercept.

Substituting the known stress condition $(\bar{\sigma}_a, \tau_a)$, given by equations 5 and 8, into equation 14 yields:

$$\begin{aligned} \gamma_t Z_w \sin \theta \cos \theta + \gamma_{sat} (Z - Z_w) \sin \theta \cos \theta \\ = \gamma_t Z_w \cos^2 \theta \tan \theta + \gamma_b (Z - Z_w) \cos^2 \theta \tan \theta + b. \end{aligned} \quad (15)$$

Solving for b from equation 15:

$$b = (\gamma_{sat} - \gamma_b) [(Z - Z_w) \sin \theta \cos \theta]. \quad (16)$$

Recalling that $\gamma_w = (\gamma_{sat} - \gamma_b)$, equation 16 may be written as:

$$b = \gamma_w \sin \theta (Z - Z_w) \cos \theta. \quad (17)$$

Equation 17 is recognized as the equation for the seepage force per unit area, S :

$$S = \gamma_w i V = \gamma_w \sin \theta (Z - Z_w) \cos \theta. \quad (18)$$

Where:

$i = \sin \theta$ (the hydraulic gradient as shown in figure 5);

$V = (Z - Z_w) \cos \theta$ (the volume of the column of soil between the water table and plane A-A' shown in figure 2).

The intercept, b , is therefore equal to the seepage force per unit area, S . Substituting the expression for b , from equation 17, into equation 14, yields the equation for a line through point $(\bar{\sigma}_a, \tau_a)$, with a slope equal to $\tan \theta$:

$$\tau = \bar{\sigma} \tan \theta + \gamma_w (Z - Z_w) \sin \theta \cos \theta = \bar{\sigma} \tan \theta + S. \quad (19)$$

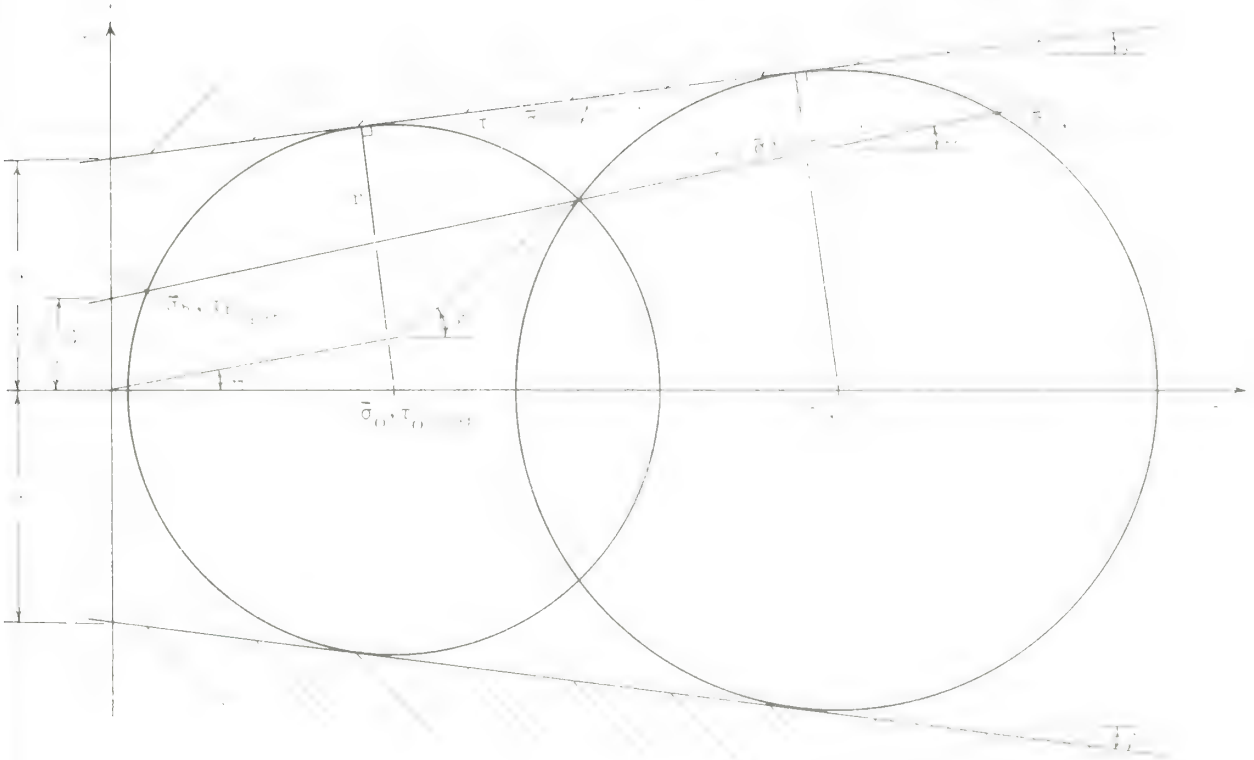


Figure 13.--Active and passive stress circles and their relations to Mohr's rupture envelope.

From equation 13 and figure 13, the equation for a leaf of the Mohr rupture envelope can be written as:

$$\tau - \bar{\sigma} \tan \phi - c = 0.$$

The normal form of equation 20 is the expression for all lines perpendicular to the leaf of the failure envelope:

$$-\frac{\bar{\sigma} \tan \phi}{\sqrt{1 + \tan^2 \phi}} + \frac{\tau}{\sqrt{1 + \tan^2 \phi}} - \frac{c}{\sqrt{1 + \tan^2 \phi}} = 0.$$

Because the stress circle is tangent to the failure envelope, the radius of the stress circle, r , is perpendicular to the failure envelope at the point of tangency. Noting that τ_0 equals zero, the length of the radius is found by substituting the coordinates for the center of the circle of stresses $(\bar{\sigma}_0, \tau_0)$ into equation 21:

$$r = \left| -\frac{\bar{\sigma}_0 \tan \phi}{\sqrt{1 + \tan^2 \phi}} - \frac{c}{\sqrt{1 + \tan^2 \phi}} \right|.$$

The general equation for the circle of stresses passing through point $(\bar{\sigma}_a, \tau_a)$ is, therefore:

$$(\bar{\sigma} - \bar{\sigma}_O)^2 + \tau^2 - \frac{(\bar{\sigma}_O \tan \phi + c)^2}{1 + \tan^2 \phi} = 0. \quad (23)$$

The origin of planes, $(\bar{\sigma}_b, \tau_b)$, is defined by the intersection of the circle of stresses and the line parallel to the ground surface that passes through the point $(\bar{\sigma}_a, \tau_a)$. The general equation for this intersection is found by substituting the expression for τ from equation 19 into equation 23:

$$(\bar{\sigma} - \bar{\sigma}_O)^2 + (\bar{\sigma} \tan \theta + S)^2 - \frac{(\bar{\sigma}_O \tan \phi + c)^2}{1 + \tan^2 \phi} = 0. \quad (24)$$

Equation 24 can be rewritten to yield a quadratic in $\bar{\sigma}$:

$$\begin{aligned} & \bar{\sigma}^2(1 + \tan^2 \theta) + \bar{\sigma}(-2\bar{\sigma}_O + 2\tan \theta S) \\ & + \bar{\sigma}_O^2 + S^2 - \frac{(\bar{\sigma}_O \tan \phi + c)^2}{1 + \tan^2 \phi} = 0. \end{aligned} \quad (25)$$

Equation 25 will lead to two solutions for $\bar{\sigma}$: one solution $(\bar{\sigma}_a)$ will correspond to the point of known stress $(\bar{\sigma}_a, \tau_a)$; and the other solution $(\bar{\sigma}_b)$ will correspond to the origin of planes $(\bar{\sigma}_b, \tau_b)$. Equation 25 can be solved by means of a "sum of roots" solution (Rosenbach and others 1958), with the following result:

$$\bar{\sigma}_a + \bar{\sigma}_b = \frac{2\bar{\sigma}_O - 2\tan \theta S}{1 + \tan^2 \theta}. \quad (26)$$

By substituting $\bar{\sigma}_a$ for $\bar{\sigma}$, equation 24 can be rewritten as a quadratic in $\bar{\sigma}_O$, in which $\bar{\sigma}_O$ is the only unknown:

$$\begin{aligned} & \bar{\sigma}_O^2 + \bar{\sigma}_O(-2\bar{\sigma}_a - 2\bar{\sigma}_a \tan^2 \phi - 2\tan \phi c) \\ & + \bar{\sigma}_a^2(1 + \tan^2 \phi + \tan^2 \theta + \tan^2 \phi \tan^2 \theta) \\ & + 2\bar{\sigma}_a \tan \theta S(1 + \tan^2 \phi) + S^2(1 + \tan^2 \phi) - c^2 = 0. \end{aligned} \quad (27)$$

Solving equation 27 by means of the "quadratic equation" and rearranging, yields:

$$\begin{aligned} \bar{\sigma}_O = & \bar{\sigma}_a(1 + \tan^2 \phi) + \tan \phi c \pm \left\{ [-\bar{\sigma}_a(1 + \tan^2 \phi) - \tan \phi c]^2 \right. \\ & - [\bar{\sigma}_a^2(1 + \tan^2 \phi + \tan^2 \theta + \tan^2 \phi \tan^2 \theta) \\ & \left. + 2\bar{\sigma}_a \tan \theta S(1 + \tan^2 \phi) + S^2(1 + \tan^2 \phi) - c^2] \right\}^{\frac{1}{2}}. \end{aligned} \quad (28)$$

The positive root defines the center of the passive stress circle and the negative root defines the center of the active stress circle.

Solving for $\bar{\sigma}_b$ in equation 26, yields:

$$\bar{\tau}_b = \frac{2\bar{\tau}_0 - 2\tan\theta S}{(1+\tan^2\theta)} - \bar{\sigma}_a \quad (29)$$

Where: $\bar{\sigma}_0$ is defined by equation 28;

S is defined by equation 18; and

$\bar{\sigma}_a$ is defined by equation 8.

Because $\bar{\sigma}_0$ has two roots, it follows that $\bar{\sigma}_b$ will also have two roots, one for the active origin of planes and the other for the passive origin of planes, as shown in figure 13. An equation for τ_b can be developed, in terms of the defined quantity, $\bar{\sigma}_b$, by substituting $\bar{\sigma}_b$ into equation 19:

$$\tau_b = \bar{\sigma}_b \tan\theta + \gamma_w(Z-Z_w)\sin\theta\cos\theta = \bar{\sigma}_b \tan\theta + S. \quad (30)$$

With the expressions, equations 29 and 30, defining the origin of planes, the state of stress, $(\bar{\sigma}_c, \tau_c)$, on any plane of investigation, α , can now be obtained. The conventions and notation for the typical stress circle are shown in figure 14.

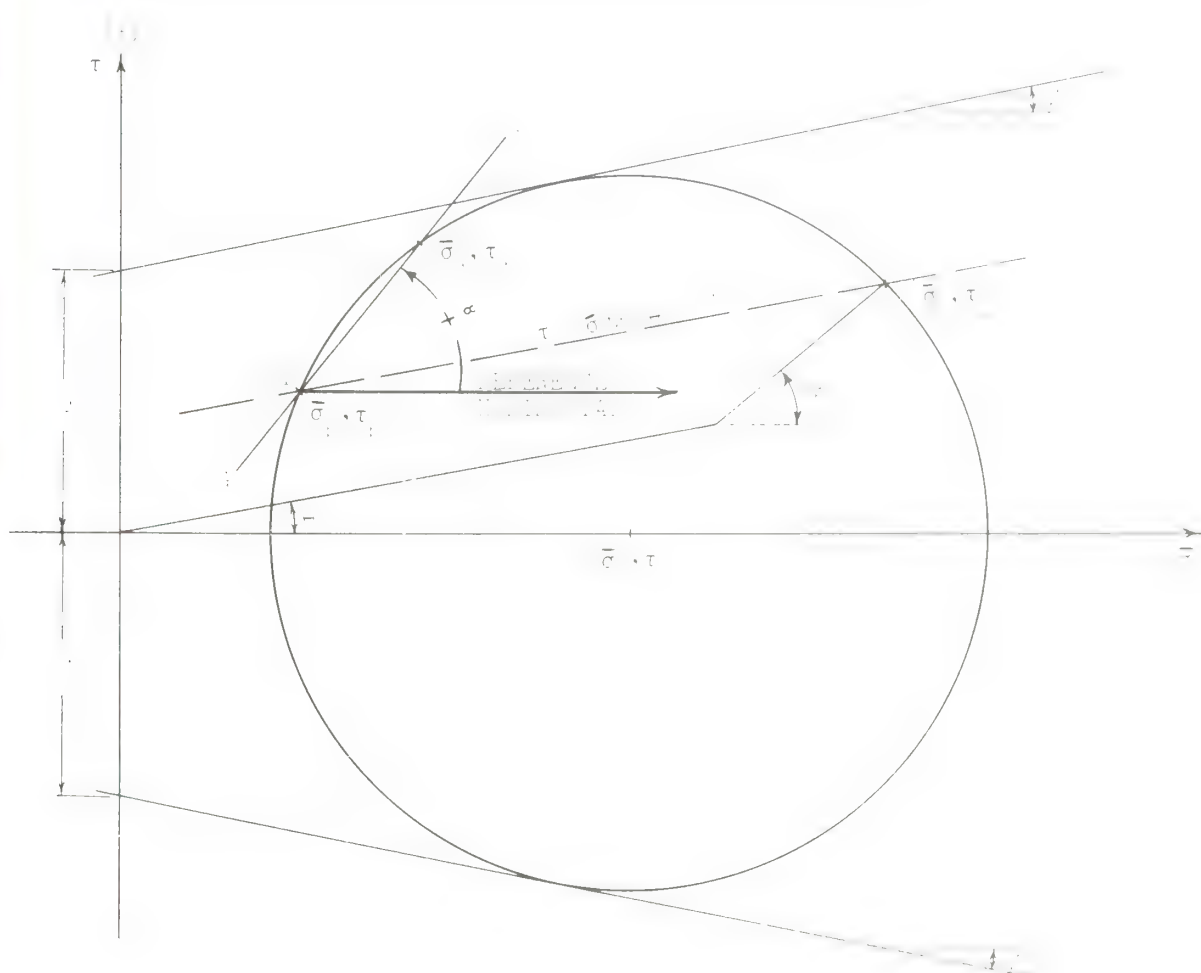


Figure 14. -- Typical stress circle.

The general equation for the slope of the line, GH, that passes through point $(\bar{\sigma}_b, \tau_b)$, as shown in figure 14, is:

$$\tan \alpha = \frac{\tau - \tau_b}{\bar{\sigma} - \bar{\sigma}_b} . \quad (31)$$

Therefore, the equation of the line that passes through point $(\bar{\sigma}_b, \tau_b)$, and has a slope of α , is:

$$\tau = \tau_b + (\bar{\sigma} - \bar{\sigma}_b) \tan \alpha . \quad (32)$$

The state of stress on a plane that is oriented at an angle α can be obtained by developing an equation for the intersection of the stress circle and line GH. The equation for the intersection is found by substituting the expression for τ from equation 32 into equation 23:

$$(\bar{\sigma} - \bar{\sigma}_o)^2 + [\tau_b + (\bar{\sigma} - \bar{\sigma}_b) \tan \alpha]^2 - \frac{(\bar{\sigma}_o \tan \phi + c)^2}{1 + \tan^2 \phi} = 0 . \quad (33)$$

Equation 33 can be rewritten to yield a quadratic in $\bar{\sigma}$:

$$\begin{aligned} & \bar{\sigma}^2(1 + \tan^2 \alpha) + \bar{\sigma}(-2\bar{\sigma}_o + 2\tau_b \tan \alpha - 2\bar{\sigma}_b \tan^2 \alpha) \\ & + (\bar{\sigma}_o^2 + \tau_b^2 - 2\tau_b \bar{\sigma}_b \tan \alpha + \bar{\sigma}_b^2 \tan^2 \alpha) \\ & - \frac{(\bar{\sigma}_o \tan \phi + c)^2}{1 + \tan^2 \phi} = 0 . \end{aligned} \quad (34)$$

The two roots of equation 34 are determined by the "sum of roots" technique. One root is the normal stress at the origin of planes, $\bar{\sigma}_b$, while the other root is the normal stress on the plane of investigation, $\bar{\sigma}_c$:

$$\bar{\sigma}_c = \frac{2\bar{\sigma}_o - 2\tau_b \tan \alpha + 2\bar{\sigma}_b \tan^2 \alpha}{1 + \tan^2 \alpha} - \bar{\sigma}_b . \quad (35)$$

Because all terms on the right-hand side of equation 35 have been previously defined, the only unknown, $\bar{\sigma}_c$, is expressed in terms of defined parameters. An alternate form of equation 35 can be written by substituting the expression for τ_b from equation 30 into equation 35:

$$\bar{\sigma}_c = \frac{2\bar{\sigma}_o + \bar{\sigma}_b(-1 + \tan^2 \alpha - 2 \tan \alpha \tan \theta) - 2 \tan \alpha S}{1 + \tan^2 \alpha} . \quad (36)$$

An equation for τ_c can be developed by substituting $\bar{\sigma}_c$, into equation 32:

$$\tau_c = \tau_b + (\bar{\sigma}_c - \bar{\sigma}_b) \tan \alpha . \quad (37)$$

Equations 36 and 37 are general equations for calculating the normal and tangential stresses on a plane at any inclination, when the soil within an infinite slope is at the active or passive state of stress.

EQUATION VERIFICATION

Equation Compatibility

To verify this analytical development, the equations presented will be compared to those developed by other investigators. Martin (1961) has shown that his solution for active and passive pressures on a vertical plane agrees with developments by various other investigators. Because this paper is an extension of Martin's work, demonstrating that the equations presented herein agree with Martin's equations would also imply agreement with developments by other investigators.

Compatibility is proved by showing that equation 35, for the normal stress $\bar{\sigma}_c$, reduces to Martin's equation for normal stress; therefore the restrictions (no seepage forces and stresses on a vertical plane) on Martin's development must be applied to equation 35.

Recalling the trigonometric identity, $(1+\tan^2\alpha)=(\frac{1}{\cos^2\alpha})$, equation 35 can be rewritten:

$$\bar{\sigma}_c = 2\bar{\sigma}_o \cos^2\alpha - 2\tau_b \sin\alpha \cos\alpha + 2\bar{\tau}_b \sin^2\alpha - \bar{\tau}_b. \quad (38)$$

The normal stress on a vertical plane is found by setting α equal to 90° in equation 38:

$$\bar{\sigma}_c = \bar{\sigma}_b. \quad (39)$$

Therefore, the normal stress on a vertical plane is equal to the normal stress at the origin of planes, $\bar{\sigma}_b$ in equation 29. $\bar{\sigma}_b$ can be adapted to the no seepage force condition by setting S equal to zero in equation 29:

$$\bar{\sigma}_b = \frac{2\bar{\sigma}_o}{1+\tan^2\theta} - \bar{\tau}_a. \quad (40)$$

Substituting the expression for $\bar{\sigma}_o$ from equation 28 into equation 40, and recalling that $\bar{\sigma}_c$ equals $\bar{\sigma}_b$ for this special case:

$$\begin{aligned} \bar{\sigma}_c = & \frac{2\bar{\tau}_a + 2\bar{\sigma}_a \tan\theta + 2c \tan\theta}{1+\tan^2\theta} \\ & + \left\{ \frac{(-2\bar{\tau}_a - 2\bar{\sigma}_a \tan\theta - 2c \tan\theta)^2}{(1+\tan^2\theta)^2} \right. \\ & \left. - \frac{4\left[\bar{\tau}_a^2(1+\tan^2\theta + \tan\theta + \tan\theta \tan\theta) - c^2\right]}{(1+\tan^2\theta)^2} \right\} \\ & - \bar{\tau}_a. \end{aligned} \quad (41)$$

Equation 41 is exactly the same (except for notation) as Martin's equation for the normal stress on a vertical plane. Therefore, the general equations given in this analytical development agree with equations given by other investigators for their more restrictive conditions.

Critical Depth

The soil properties, slope of ground surface, depth of the water table, and depth to the plane of investigation will all affect the stress condition $(\bar{\sigma}_a, \tau_a)$. Active and passive stress circles can be drawn through point $(\bar{\sigma}_a, \tau_a)$ if, and only if, this stress condition remains within the Mohr envelope. The Mohr diagram, with the stress conditions $(\bar{\sigma}_a, \tau_a)$ superimposed, shows conditions where failure is impending. The critical depth can be defined as the depth at which the stress condition on plane A-A' is equal to the strength of the soil. When the stress condition $(\bar{\sigma}_a, \tau_a)$ lies on the Mohr envelope, only one stress circle may be drawn. For this condition, the active and passive stress circles coincide, and failure is impending.

The stress on plane A-A', $(\bar{\sigma}_a, \tau_a)$, at the critical depth, in a cohesive material, is shown in figure 15. If:

1. $\phi > \beta > \theta$, no critical depth exists;
2. $\beta > \phi > \theta$, a critical depth exists; and
3. $\beta > \theta > \phi$, a critical depth exists.

The stress on plane A-A', $(\bar{\sigma}_a, \tau_a)$, at the critical depth, in a cohesionless material, is shown in figure 16. If:

1. $\phi > \beta > \theta$, no critical depth exists;
2. $\phi = \beta > \theta$, no critical depth exists;
3. $\phi = \beta = \theta$, a failure condition exists at all depths;
4. $\beta > \phi > \theta$, a critical depth exists; and
5. $\beta > \theta > \phi$, a failure condition exists at all depths.

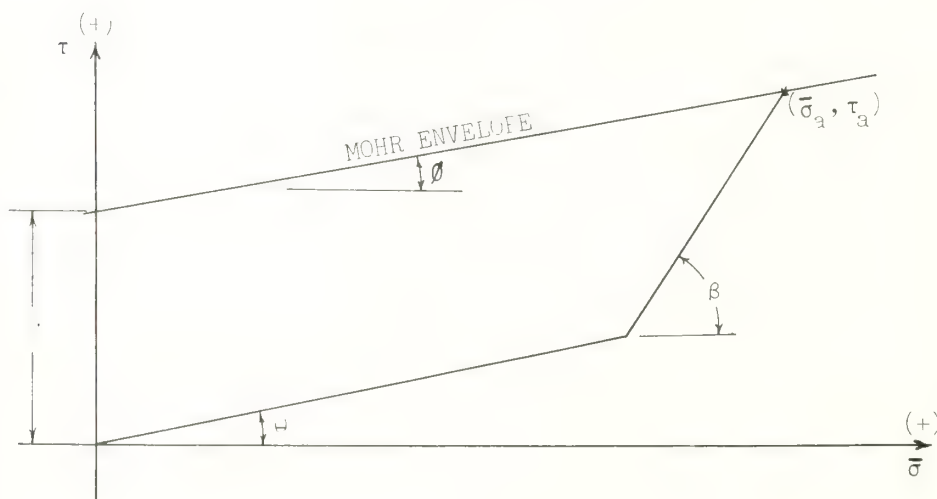


Figure 15.--Stress condition at the critical depth when the unit cohesion is greater than zero.

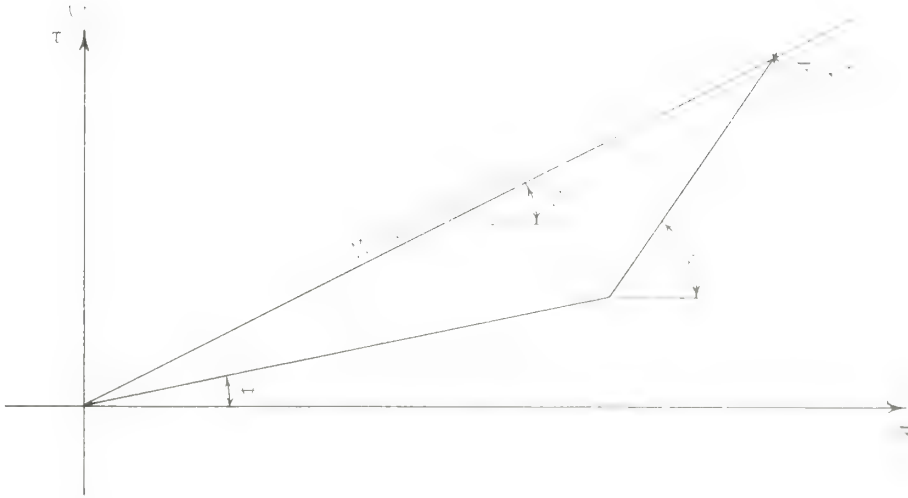


Figure 16.--Stress condition at the critical depth when the unit cohesion equals zero.

The equations for critical depth are found by equating stress conditions to strength conditions. Equating the right-hand sides of equations 19 and 13, yields:

$$\bar{\sigma} \tan \theta + S = \bar{\sigma} \tan \phi + c. \tag{42}$$

Substituting the expressions for $\bar{\sigma}_a$ and S from equation 8 and 18 into equation 42 and solving for the critical depth, Z_{cr} , yields:

$$Z_{cr} = Z_w + \frac{c - \gamma_t Z_w \cos^2 \theta (\tan \theta - \tan \phi)}{\gamma_b \cos^2 \theta (\tan \theta - \tan \phi) + \gamma_w \sin \theta \cos \theta}. \tag{43}$$

For the special case of no ground water ($Z - Z_w$) is zero. Solving equations 8 and 18 for Z_{cr} :

$$Z_{cr} = \frac{c}{\gamma_t \cos^2 \theta (\tan \theta - \tan \phi)}. \tag{44}$$

which is the critical depth for the special case of no ground water. Note that in all the equations presented, a slope will be stable as long as the depth of the soil material is less than the critical depth.

Figure 17 shows the stress condition at the critical depth for a typical slope. This figure is also helpful for visualizing the expressions presented in previous chapters for the stresses acting on plane A-A'.

NONDIMENSIONAL FORMULATION

To reduce the number of variables, the equations presented in the analytical development were made dimensionless. Equation 36 for $\bar{\sigma}_c$ was expanded and divided by c , the unit cohesion, to determine the basic dimensionless parameters:

$$1. \quad Y = \frac{\gamma_t Z_w}{c}$$

$$2. \quad Y' = \frac{\gamma_b (Z - Z_w)}{c}$$

$$3. \quad X = \frac{\gamma_w (Z - Z_w)}{c} = Y' \left(\frac{\gamma_w}{\gamma_b} \right).$$

The development of the nondimensional expressions parallels the analytical development. It was necessary to define additional parameters for the equations that lead to the final nondimensional expressions for the normal and tangential stresses. Because each nondimensionalized equation has an analog in the analytical development, the equations are presented with few details.

The nondimensional form of the effective normal stress on plane A-A', $\bar{\sigma}_q$, is obtained from equation 8:

$$N'_a = \frac{\tau}{c} = Y \cos \alpha + Y' \cos \alpha. \quad (45)$$

The nondimensional form of the seepage force per unit area, S , is obtained from equation 18:

$$v = \frac{S}{c} = X \sin \alpha \cos \alpha + Y' \left(\frac{\gamma_w}{\gamma_b} \right) \sin \alpha \cos \alpha. \quad (46)$$

The nondimensional form of the tangential stress on plane A-A', τ_q , is obtained from equation 5:

$$T'_a = \frac{\tau}{c} = N'_a \tan \alpha + X \sin \alpha \cos \alpha. \quad (47)$$

The nondimensional form of the center of the stress circle, $\bar{\sigma}_O$, is obtained from equation 28:

$$\begin{aligned} N''_O = \frac{\bar{\sigma}_O}{c} = & N''_a(1+\tan^2\phi) + \tan\phi \\ & \pm \left\{ [N''_a(1+\tan^2\phi)^2 + 2N''_a(1+\tan^2\phi)\tan\phi + \tan^2\phi] \right. \\ & - N''_a^2(1+\tan^2\phi+\tan^2\theta+\tan^2\phi\tan^2\theta) - 2N''_av\tan\theta(1+\tan^2\phi) \\ & \left. - v^2(1+\tan^2\phi) + 1 \right\}^{\frac{1}{2}}. \end{aligned} \quad (48)$$

The nondimensional form of the normal stress at the origin of planes, $\bar{\sigma}_b$, is obtained from equation 29:

$$N''_b = \frac{\bar{\sigma}_b}{c} = 2\cos^2\theta(N''_O - v\tan\theta) - N''_a. \quad (49)$$

The nondimensional form of the tangential stress at the origin of planes, τ_b , is obtained from equation 30:

$$T''_b = \frac{\tau_b}{c} = N''_b\tan\theta + v. \quad (50)$$

The nondimensional form of the normal stress on a plane at the depth of investigation oriented at angle α , $\bar{\sigma}_c$, is obtained from equation 36:

$$N''_c = \frac{\bar{\sigma}_c}{c} = \cos^2\alpha [2N''_O + N''_b(-1+\tan^2\alpha - 2\tan\alpha\tan\theta) - 2v\tan\alpha]. \quad (51)$$

The nondimensional form of the tangential stress on a plane at the depth of investigation oriented at angle α , τ_c , is obtained from equation 37:

$$T''_c = \frac{\tau_c}{c} = T''_b + (N''_c - N''_b)\tan\alpha. \quad (52)$$

Figure 18 shows the notation on a nondimensional Mohr's diagram, which is analogous to figure 13.

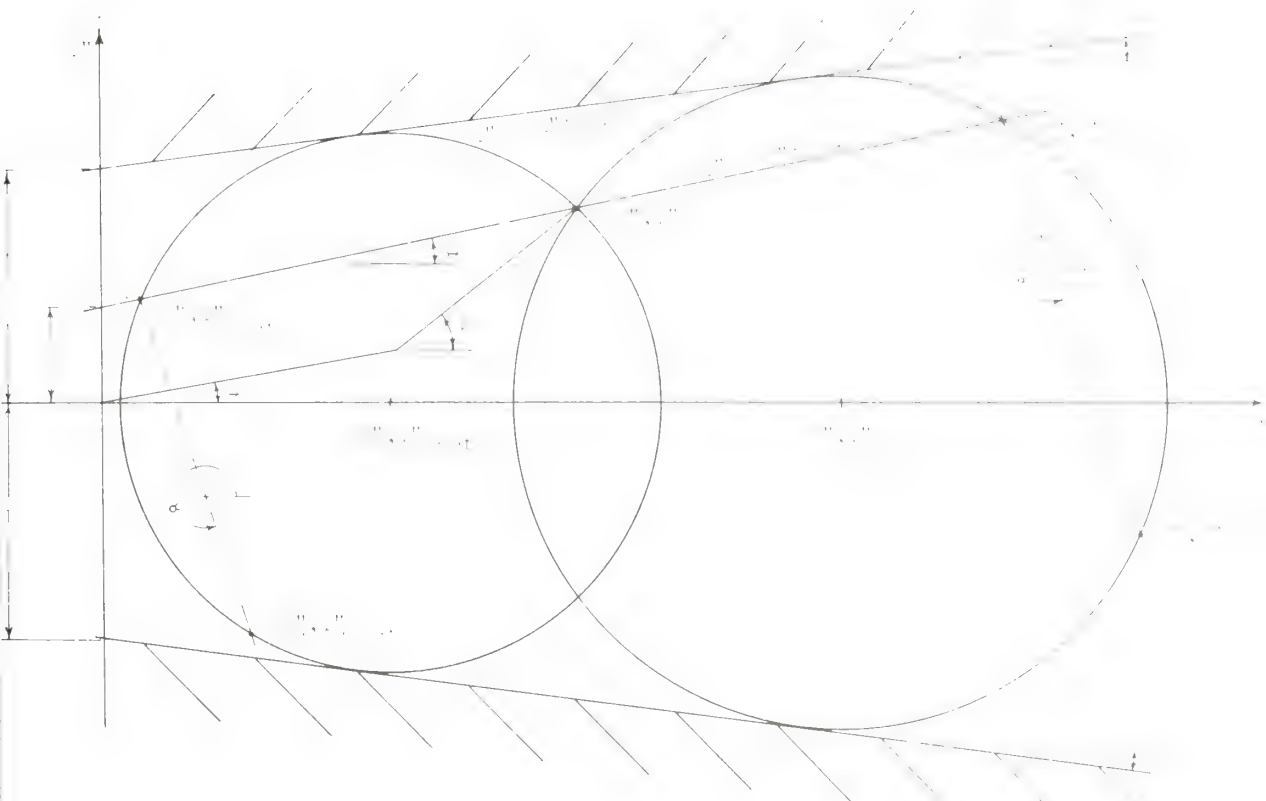


Figure 18.--Nondimensional Mohr diagram.

The equations for the nondimensional analogy of the critical depth were developed in the same manner as equations 42 through 44. The critical depth in terms of the nondimensional parameters is:

$$(Y + Y')_{cr} = \frac{1 - X \sin \theta \cos \theta}{\cos^2 \theta (\tan \theta - \tan \phi)} \quad (55)$$

where: $(Y + Y')_{cr}$ is the nondimensional form of the critical depth. For the special case of no ground water table, the nondimensional critical depth is:

$$Y_{cr} = \frac{1}{\cos^2 \theta (\tan \theta - \tan \phi)} \quad (56)$$

TABULATED RESULTS

Dimensional Form

The equations presented in the analytical development were programed for solution on a digital computer. The slope inclination θ , the depth to the water table Z_w , the depth of investigation Z , and the soil properties ϕ , c , γ_t , and γ_b were assigned appropriate values, and the active and passive stresses acting on a plane at inclination α were determined. The angle α was incremented from 0° to 360° to solve for the stress on selected planes. A listing of this computer program is shown in the Appendix, and typical results are shown in tables 2 and 3.

Nondimensional Form

The equations presented in the nondimensional formulation were programed for an IBM 1620, Model II, digital computer. The parameters ϕ , θ , Y , and Y' , were assigned various levels, and the nondimensional values representing the active and passive stresses, acting on a plane at inclination α , were determined. The angle α was incremented from 0° to 360° in order to solve for the stress on selected planes. The parameters ϕ , θ , Y , and Y' , were then systematically varied to provide a comprehensive tabulation of results. Typical results are presented in tables 4 and 5.

Table 2.--Active stresses on plane of investigation for hypothetical soil and slope values

Depth to plane of investigation, feet	$\frac{\sigma}{\gamma H}$	Angle of plane of investigation, degrees	Normal effective stress on plane of investigation, lb./sq. ft.	Tangential effective stress on plane of investigation, lb./sq. ft.
10	15.0	15.0	926.1	172.0
	30.0	30.0	722.9	586.4
	45.0	45.0	559.7	845.7
	60.0	60.0	420.7	874.9
	75.0	75.0	355.1	671.6
	90.0	90.0	288.4	288.4
	105.0	105.0	825.6	172.0
	300.0	300.0	620.5	586.4
	315.0	315.0	257.1	845.7
	330.0	330.0	225.5	874.9
	345.0	345.0	657.7	671.6
	360.0	360.0	895.0	288.4
20	15.0	15.0	1861.7	451.6
	30.0	30.0	1485.1	961.5
	45.0	45.0	900.4	1215.5
	60.0	60.0	269.6	1140.5
	75.0	75.0	240.0	761.9
	90.0	90.0	492.2	179.1
	105.0	105.0	419.2	451.6
	300.0	300.0	40.6	961.5
	315.0	315.0	542.1	1215.5
	330.0	330.0	1172.8	1140.5
	345.0	345.0	1682.6	761.9
	360.0	360.0	1984.7	451.6

Unit cohesion, $c = 1000$ lb./ft.
Depth to water table, $z_w = 20$ ft.
Angle of internal friction, $\phi = 20^\circ$
Ground surface inclination, $\alpha = 20^\circ$
Unit weight of soil, $\gamma = 120$ lb./cu. ft.
Ground water table, $z_w = 20$ ft.
Unit weight of water, $\gamma_w = 62.4$ lb./cu. ft.

Plane of investigation parallel to the horizontal.

Table 3.--Passive stresses on plane of investigation for hypothetical soil and slope values

Depth to plane of investigation, feet	$\frac{\sigma}{\gamma H}$	Angle of plane of investigation, degrees	Normal effective stress on plane of investigation, lb./sq. ft.	Tangential effective stress on plane of investigation, lb./sq. ft.
10	150.0	150.0	4221.8	2480.1
	165.0	165.0	2879.4	2529.7
	180.0	180.0	1692.0	1901.4
	195.0	195.0	977.9	765.6
	210.0	210.0	928.5	578.7
	225.0	225.0	1556.6	1766.0
	240.0	240.0	2694.4	2480.1
	255.0	255.0	4036.8	2529.7
	270.0	270.0	5224.2	1901.4
	285.0	285.0	5935.5	765.6
	300.0	300.0	5987.8	578.7
	315.0	315.0	5559.6	1766.0
20	150.0	150.0	6562.2	3215.8
	165.0	165.0	4591.9	3393.0
	180.0	180.0	2969.2	2662.9
	195.0	195.0	1928.9	1219.4
	210.0	210.0	1749.8	550.9
	225.0	225.0	2479.8	2175.6
	240.0	240.0	3925.4	3215.8
	255.0	255.0	5693.7	3393.0
	270.0	270.0	7516.4	2662.9
	285.0	285.0	8556.7	1219.4
	300.0	300.0	8735.8	550.9
	315.0	315.0	7845.8	2175.6

Unit cohesion, $c = 1000$ lb./ft.
Depth to water table, $z_w = 20$ ft.
Angle of internal friction, $\phi = 20^\circ$
Ground surface inclination, $\alpha = 20^\circ$
Unit weight of soil, $\gamma = 120$ lb./cu. ft.
Ground water table, $z_w = 20$ ft.
Unit weight of water, $\gamma_w = 62.4$ lb./cu. ft.

Plane of investigation parallel to the horizontal.

Table 4. -- Nondimensional active stresses for hypothetical
: α is angle

γ_2/γ_1	γ_3/γ_1	γ_4/γ_1	N_c^0/γ_1	T_c^0/γ_1
1.00	0.50	15.0	1.2530	0.4103
		30.0	.9056	.8113
		45.0	.4217	.9949
		60.0	-.0896	.9119
		75.0	-.4902	.5846
		90.0	-.6758	.1006
		285.0	-.5908	-.4103
		300.0	-.2635	-.8113
		315.0	.2204	-.9949
		330.0	.7313	-.9119
		345.0	1.1523	-.5846
		360.0	1.3160	-.1006
1.00	.60	15.0	1.5433	.6878
		30.0	1.1021	.9586
		45.0	.5846	.9725
		60.0	.1296	.7258
		75.0	-.1411	.2846
		270.0	-.1550	-.2328
		285.0	.0916	-.6878
		300.0	.5328	-.9586
		315.0	1.0503	-.9725
		330.0	1.5054	-.7258
		345.0	1.7761	-.2846
		360.0	1.7900	.2328

- 1/ Angle of internal friction, $\phi = 0^\circ$
- 2/ γ is a nondimensional parameter ($\gamma = \gamma_t z_w/c$).
- 3/ γ' is a nondimensional parameter ($\gamma' = \gamma_b (2-z_w)/c$).
- 4/ α is the angle of the plane of investigation as measured counterclockwise from the horizontal.
- 5/ N_c^0 is the nondimensional form of the effective stress on the plane of investigation.
- 6/ T_c^0 is the nondimensional form of the tangential effective stress on the plane of investigation.

Table 5. -- Nondimensional passive stresses for hypothetical
: α is angle

γ_2/γ_1	γ_3/γ_1	γ_4/γ_1	N_c^0/γ_1	T_c^0/γ_1
1.00	0.50	165.0	2.2204	0.9693
		180.0	1.7029	.9623
		195.0	1.2581	.6974
		210.0	1.0054	.2457
		225.0	1.0124	-.2718
		240.0	1.2772	-.7166
		255.0	1.7290	-.9693
		270.0	2.2466	-.9623
		285.0	2.6913	-.6974
		300.0	2.9441	-.2457
		315.0	2.9371	.2718
		330.0	2.6722	.7166
1.00	.60	195.0	1.5614	.8946
		210.0	1.1739	.5514
		225.0	1.0099	.0604
		240.0	1.1135	-.4467
		255.0	1.4567	-.8342
		270.0	1.9477	-.9981
		285.0	2.4549	-.8946
		300.0	2.8423	-.5514
		315.0	3.0063	-.0604
		330.0	2.9028	.4467
		345.0	2.5595	.8342
		360.0	2.0685	.9981

- 1/ Angle of internal friction, $\phi = 0^\circ$
- 2/ γ is a nondimensional parameter ($\gamma = \gamma_t z_w/c$).
- 3/ γ' is a nondimensional parameter ($\gamma' = \gamma_b (2-z_w)/c$).
- 4/ α is the angle of the plane of investigation as measured counterclockwise from the horizontal.
- 5/ N_c^0 is the nondimensional form of the effective stress on the plane of investigation.
- 6/ T_c^0 is the nondimensional form of the tangential effective stress on the plane of investigation.

As an example, the resulting nondimensional tables may be used as follows:

Let: $\phi = 0^\circ$

$\theta = 20^\circ$

$Z_w = 4.0 \text{ ft}$

$Z = 6.3 \text{ ft}$

$c = 320 \text{ lb/ft}^2$

$\gamma_b = 41.60 \text{ lb/ft}^3$

$\gamma_t = 80 \text{ lb/ft}^3$

$\alpha = 75^\circ$

It is desired that the active stress for the above conditions be determined. The nondimensional parameters Y and Y' are calculated as follows:

$$Y = \frac{\gamma_t Z_w}{c} = \frac{(80)(4.0)}{320} = 1.0,$$

$$Y' = \frac{\gamma_b (Z - Z_w)}{c} = \frac{(41.60)(6.3 - 4.0)}{320} \approx 0.5.$$

The upper portion of table 4 is applicable for the example values of ϕ , θ , Y , and Y' ; therefore, values are obtained for parameters N''_c and T''_c from the line corresponding to the α value of 75° :

$$N''_c = -0.4902,$$

$$T''_c = 0.5846.$$

Since $N''_c = \frac{\bar{\sigma}_c}{c}$, then $\bar{\sigma}_c = cN''_c = (320)(-0.4902) = -157.0 \text{ lb/ft}^2$, which is the active effective normal stress on a plane inclined at an angle α of 75° . Since $T''_c = \frac{\tau_c}{c}$, then $\tau_c = cT''_c = (320)(0.5846) = 186.8 \text{ lb/ft}^2$, which is the tangential stress on a plane inclined at an angle α of 75° .

CONCLUSIONS

When the Rankine assumptions are to be used to determine earth pressures, the equations presented herein will yield the active and passive earth pressures, on a plane at any inclination, within an infinite slope having a water table that is parallel to the ground surface.

The solutions presented do not include pressures from freezing or swelling of soil hydrostatic water conditions, and so on. The solutions are documented for use when the Rankine assumptions are valid; however, the author does not advocate the use of Rankine's theory in cases where conjugate stresses do not exist.

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APPENDIX

*****DIMENSIONAL COMPUTER PROGRAM*****

```

C      STRESS ON ANY PLANE - INFINITE SLIP THEORY - W. HARTMAN
C*****
      READ 1, COHES, PHI0, GAMMA, THETA0
C COHES=COHESION P.S.F., PHI=FRICITION ANGLE IN DEGREE
C GAMMA=UNIT WEIGHT OF SOIL ABOVE W.T. IN P.S.F.
C THETA0=INCLINATION OF PLANE IN DEGREE
      1 FORMAT (4F10.1)
      PRINT 2, COHES, PHI0, GAMMA, THETA0
      20FORMAT (10X,10HCOHESION =,F6.1,4H PCF, 2X,6HPHI =,F6.1,5H DEG.,
      17X,7HGAMMA =,F6.1,4H PCF, 2X,8HTHETA =,F6.1,5H DEG.)
      READ 3, GAMMA0, ZW
C GAMMA0=BUOYANT UNIT WEIGHT, ZW=VERTICAL DEPTH TO W.T.
      3 FORMAT (2F10.1)
      READ 33,N
C N IS INCREMENT OF ALPHA IN DEGREES
      33 FORMAT (I10)
      READ 34, L,M
C L IS INCREMENT OF DEPTH M IS MAXIMUM DEPTH
      34 FORMAT (2I10)
      PRINT 4,N,GAMMA0,ZW
      4 FORMAT (39X,3HN =,I5,15X,6HGAMMA0 =,F6.1,4H PCF,11X,4H ZW =,F6.1,
      14H FT.)
      PRINT 9
      9 FORMAT (1HC,15X,46H*****
      PI=3.14159
      PHI=(PHI0*PI)/180.
      THETA= THETA0*PI/180.
      GAMMAW=62.4
      A=COSF(THETA)
      A2=A*A
      B=SINF(THETA)
      TANT=B/A
      TANT2=TANT*TANT
      H=SINF(PHI)/COSF(PHI)
      D=1.+H*H
      GA2=GAMMA*A2
      GA2D=GA2*D
      COHESH=COHES*H
      72 DO 51 IZ=L,M,L
      Z=IZ
C Z=TOTAL DEPTH TO PLANE IN FEET
      IF (Z-ZW)20, 20, 30
      20 Z1=Z
      Z2=0.
  
```

```

      GO TO 5
      30 Z1=ZW
C     Z1=DEPTH OF SOILS ABOVE W.T.
      Z2=Z-ZW
C     Z2=DEPTH OF SOILS BELOW W.T.
      S=(Z1*GAMMA+Z2*GAMMAW)*A2
C     SIG1=NORMAL INTERGRANULAR STRESS ON PLANE INCLINED AT THETA
      S=S+GAMMAW*Z2*A
      T1=SIG1*TANT+S
C     T1=SHEARING STRESS ON PLANE INCLINED AT THETA
      B00=SIG1*D+COHESH
      B00=((-SIG1*D-COHESH)**2)-((SIG1*SIG1)*(D+TANT2+H*H*TANT2)
      1+2.*SIG1*TANT*S*D+S*S*D-COHES*COHES)
      IF (B00) 1001,1002,1003
1001 PRINT 1003,7
1003 FORMAT (1H1,3H Z=,F5.1,68H*** FAILURE CONDITIONS EXIST AT THIS DEP
      1TH WITH ABOVE PROPERTIES ***)
1004 GO TO 1005
1002 B0=SQRT(B00)
      SIG0A=G0-B0
C     SIG0A=CENTER OF ACTIVE STRESS CIRCLE
      SIG0P=G0+B0
C     SIG0P=CENTER OF PASSIVE STRESS CIRCLE
      SIG2A=((2.*SIG0A-2.*TANT*S)/(1.+TANT2))-SIG1
C     SIG2A=NORMAL INTERGRANULAR STRESS AT ORIGIN OF PLANES FOR ACTIVE CASE
      SIG2P=((2.*SIG0P-2.*TANT*S)/(1.+TANT2))-SIG1
C     SIG2P=NORMAL INTERGRANULAR STRESS AT ORIGIN OF PLANES FOR PASSIVE CASE
      T2A=SIG2A*TANT+S
C     T2A=SHEAR AT O.P. (ACTIVE CASE)
      T2P=SIG2P*TANT+S
C     T2P=SHEAR AT O.P. (PASSIVE CASE)
C     FOR ABOVE EQUATIONS REFER TO NOTES
      DELA=ATANF((-SIG2A+SIG0A)/T2A)
      IF (DELA) 50,59,60
59 IF (T2A) 50,60,60
50 DDELA=180.+(180./PI)*DELA
C     DDELA=ANGLE TANGENT MAKES WITH HORIZONTAL (ACTIVE) -NOTES 13-17
      GO TO 201
60 DDELA=(180./PI)*DELA
201 DELP=ATANF((-SIG2P+SIG0P)/T2P)
      IF (DELP) 100,209,200
209 IF (T2P) 500,400,400
200 IF (T2P) 300,400,400
400 DDDELP=(180./PI)*DELP
C     DDDELP=ANGLE TANGENT MAKES WITH HORIZONTAL (PASSIVE) -NOTES 13-17
      GO TO 80
300 DDDELP=180.+(180./PI)*DELP
      GO TO 80
100 IF (T2P) 500,600,600

```

```

500 DDPLP=180.+((180./PI)*DELP)
    GO TO 80
600 DDPLP=360.+((180./PI)*DELP)
80 PRINT 6, Z, DDELA
6 FORMAT(1H1,3H Z=,F5.1,11X,13HDELTA ACTIVE=,F6.1)
    PRINT 7
7 FORMAT(1H0//,19X,4H SIG1,13X,3HT1,13X,5H SIG2A,11X,3HT2A,13X,
13HT2A)
    PRINT 21, SIG1,T1,SIG2A,SIG2A,T2A
21 FORMAT (9X,5F16.1)
    PRINT 23
23 FORMAT(1H0,25X,5HALPHA,21X,5H SIG3A,12X,3HT3A,13X,3HT3A)
    DO 24 IALPHA=1,360,1
    ALPHAD=IALPHA
ALPHAD=ANGLE OF PLANE FOR WHICH STRESS CON ITING ARE T BE FROM
    IF (ALPHAD-DDPLA) 15,15,16
16 ALPHAD=ALPHAD+180.
    IF (ALPHAD-360.) 15,15,16
92 GO TO 125
15 ALPHA=(ALPHAD*PI)/180.
    TANA=SINF(ALPHA)/COSF(ALPHA)
    TANA2=TANA*TANA
    IF (ALPHAD-90.) 44,44,44
44 IF (ALPHAD-270.) 48,40,48
48 SIG3A=((2.*SIG1A-2.*T2A*TANA+2.*SIG2A*TANA)/(1.+TANA2))+SIG1A
SIG1A=NORMAL STRESS ON PLANE AT ANGLE ALPHA (ACTIVE)
    T3A=T2A+(SIG3A-SIG2A)*TANA
T3A=Shear stress on plane at angle ALPHA (ACTIVE)
    GO TO 41
40 SIG3A=SIG2A
    T3A=-T2A
41 P3A=SQRT((SIG3A**2)+T3A**2)
P3A=RESULTANT STRESS ON PLANE AT ANGLE ALPHA (ACTIVE)
24 PRINT 25,ALPHAD,SIG3A,T3A,P3A
25 FORMAT (1H0,24X,F6.1,9X,5F16.1)
105 PRINT 66,7,DDPLP
66 FORMAT (1H1,3H Z=,F5.1,11X,14H DELTA ACTIVE=,F6.1)
    PRINT 72
72 FORMAT(1H0//,19X,4H SIG1,13X,3HT1,13X,5H SIG2P,11X,3HT2P,13X,
13HT2P)
    PRINT 21, SIG1,T1,SIG2P,SIG2P,T2P
    PRINT 23
23 FORMAT(1H0,25X,5HALPHA,21X,5H SIG3A,12X,3HT3A,13X,3HT3A)
    IF (SIG2P-SIG2A) 81,15,82
82 GO TO IALPHA=1,360,1
    ALPHAD=IALPHA
    IF (ALPHAD-DDPLP) 115,115,116
116 ALPHAD=ALPHAD+180.

```

```

      IF (ALPHAD-360.) 115,115,71
71 GO TO 51
115 ALPHA=(ALPHAD*PI)/180.
      TANA=SINF(ALPHA)/COSF(ALPHA)
      TANA2=TANA*TANA
      IF (ALPHAD-90.) 76,74,76
76 IF (ALPHAD-270.) 73,74,73
73 SIG3P=((2.*SIG2P-2.*T2P*TANA+2.*SIG2P*TANA2)/(1.+TANA2))-SIG2P
C SIG3P=NORMAL STRESS ON PLANE AT ANGLE ALPHA -(PASSIVE)
      T3P=T2P+(SIG3P-SIG2P)*TANA
C T3P= SHEAR STRESS ON PLANE AT ANGLE ALPHA -(PASSIVE)
      GO TO 75
74 SIG3P=SIG2P
      T3P=-T2P
75 P3P=SQRTF(SIG3P*SIG3P+T3P*T3P)
C P3P=RESULTANT STRESS ON PLANE AT ANGLE ALPHA -(PASSIVE)
78 PRINT 25 ,ALPHAD,SIG3P,T3P,P3P
      GO TO 51
81 DO 84 IALPHA=N,360,N
87 ALPHAD=IALPHA
      IF (ALPHAD+180.-DDELP) 84,85,85
85 IF (ALPHAD-DDELP) 86,51,51
86 ALPHA=(ALPHAD*PI)/180.
      TANA=SINF(ALPHA)/COSF(ALPHA)
      TANA2=TANA*TANA
      IF (ALPHAD-90.) 91,99,91
91 IF (ALPHAD-270.) 93,99,93
93 SIG3P=((2.*SIG2P-2.*T2P*TANA+2.*SIG2P*TANA2)/(1.+TANA2))-SIG2P
      T3P=T2P+(SIG3P-SIG2P)*TANA
      GO TO 94
99 SIG3P=SIG2P
      T3P=-T2P
94 P3P=SQRTF(SIG3P*SIG3P+T3P*T3P)
95 PRINT 25,ALPHAD,SIG3P,T3P,P3P
84 CONTINUE
51 CONTINUE
1005 CALL EXIT
      END

```


HARTSOG, WILLIAM S., and GLEN L. MARTIN

1974. Failure conditions in infinite slopes and the resulting soil pressures, USDA For. Serv. Res. Pap. INT-149, 32 p., illus. (Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.)

The Rankine assumptions were used as a basis for developing equations for calculating active and passive earth pressures within a slope extending to infinity. The analysis considers cohesive and noncohesive soils, the angle of internal friction of the soil, seepage forces caused by a ground water table that is parallel to the ground surface, and the plane on which the stresses are to be found may be at any inclination.

KEYWORDS: infinite slope, Rankine stresses, active pressure, passive pressure, critical depth, slope stability.

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FAILURE SURFACES IN INFINITE SLOPES

Michael J. Gonsior, William S. Hartsog,
and Glen L. Martin



USDA Forest Service Research Paper INT-150, 1974
INTERMOUNTAIN FOREST & RANGE
EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHORS

MICHAEL J. GONSIOR is a Research Engineer, Forest Engineering Research, stationed at the Forestry Sciences Laboratory in Missoula, Montana. He has 8 years' experience with forest roads and logging in a research capacity.

WILLIAM S. HARTSOG is a Research Engineer, Forest Engineering Research, stationed at the Forestry Sciences Laboratory in Bozeman, Montana. He has been involved with logging and forest roads on various assignments for 6 years.

GLEN L. MARTIN is Professor and Head of the Department of Civil Engineering and Engineering Mechanics, Montana State University. He has worked for 15 years as a consultant, teacher, and researcher in the field of Soil Mechanics and Slope Stability Analysis.

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Ogden, Utah 84401
Robert W. Harris, Director

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ABSTRACT

General solutions for the failure surfaces in slopes where the assumptions of the infinite slope theory are valid have been derived. The solutions are applicable to layered systems and to any seepage conditions provided that both layering and ground water flow are parallel to ground slope. It is concluded that the infinite slope theory is of limited applicability unless modified. A modification to enable transition from the active to passive stress states is suggested.

INTRODUCTION AND PURPOSE

The infinite slope theory is based upon the assumption that a conjugate relationship exists between the vertical pressures and the lateral pressures acting on vertical planes, and that the stress conditions at any two points of equal depth are identical.

"Thus the stresses at various depths on any vertical plane must be the same as those at corresponding depths on any other vertical plane."
(Taylor 1948)

The infinite slope theory is often used to assess the stability of long, natural slopes wherein the soil properties are constant at a given depth below the surface of the slope. It appears to be most useful for situations wherein the soils are relatively uniform in depth and underlain by a stronger medium, such as bedrock.

Because no slopes are infinitely long, the applicability of this theory is a matter of judgment. It is recognized that, if failure is incipient, the lateral pressure has an active, or minimum, value at the upper end of the failing mass and a passive, or maximum, value at the lower end. In practice, however, the difference in end conditions is usually ignored, or else a simple correction factor is introduced to account for the difference.

Usually the criterion used to aid in judging applicability of the infinite slope theory is the ratio of length of slope to critical depth. A ratio of 20:1 commonly is used.

The purpose of this paper is to describe the failure surfaces in slopes that comply with the infinite slope theory and thereby, to aid the judgment of the user of this theory in assessing its applicability.

PREVIOUS WORK

The differential equation for the surface of rupture in an infinite cohesive earth slope was derived by Résal (1910) in 1910. His derivation was based upon a consideration of stress equilibrium on a triangular-shaped differential element within the slope (fig. 1), the sides of which are: (1) vertical, (2) parallel to the ground slope, and (3) parallel to the tangent of the rupture surface. In compliance with the infinite slope theory, the stress, r , acting on the vertical side of the element and the stress, p , acting on the side parallel to ground slope are conjugate. Thus, Résal's derivation enables determination of the normal ($\bar{n}$) and tangential (t) stresses acting on the assumed plane of rupture in terms of the conjugate vertical and lateral stresses. To assure compliance with the Coulomb assumption, it can be written that

$$t - \bar{n} \tan \phi = c \dots \dots \dots (1)$$

where ϕ is the angle of internal friction and c is the cohesive strength. To determine the angle of the tangent to the rupture surface, it is a simple matter to maximize the function, $t - \bar{n} \tan \phi$, by differentiating the Coulomb expression; thus

$$\frac{dt}{d\alpha'} - \frac{d\bar{n}}{d\alpha'} \tan \phi = 0 \dots \dots \dots (2)$$

where α' is the angle between the ground surface and the tangent to the rupture surface and is related to the failure surface by the expression

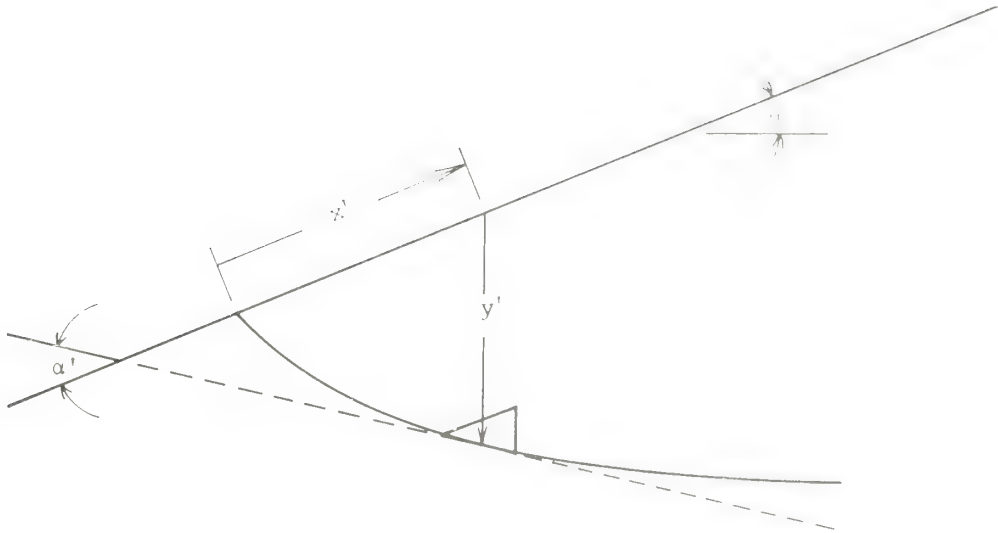
$$dx' = \frac{\cos (\theta - \alpha')}{\sin \alpha'} dy' \dots \dots \dots (3)$$

where x' is the distance from the intersection of the rupture surface with the ground surface to the point of consideration measured parallel to the ground surface, y' is the vertical distance from ground surface to the point of consideration, and θ is the slope of the ground surface.

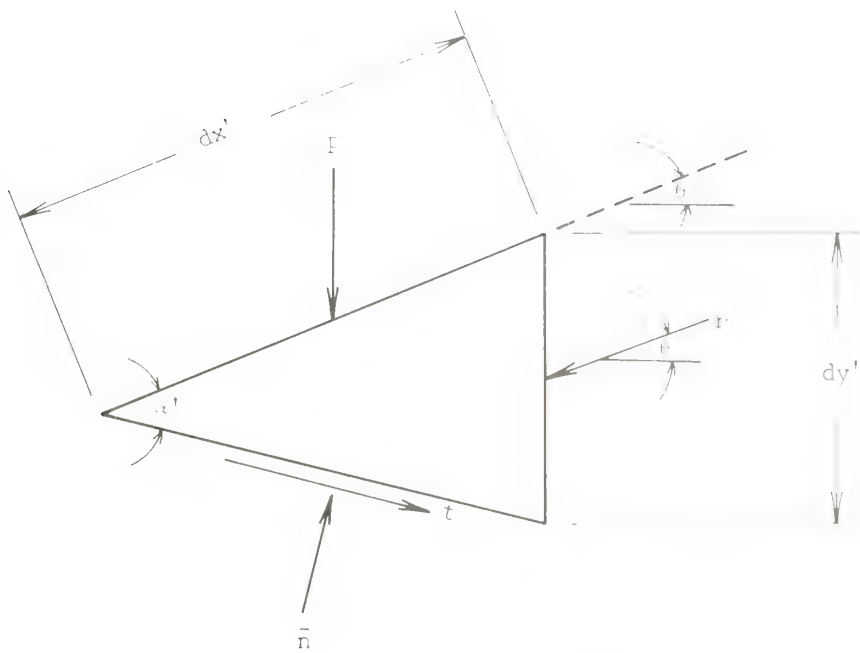
By substituting the values of t and $\bar{n}$ (determined from the stress equilibrium considerations and expressed in terms of p and r) into the above equations, Résal was led to the differential equation

$$\begin{aligned} & - \cos (\alpha' - \theta) \sin (\alpha' - \theta + \phi) \cos (2\alpha' + \phi) \\ & + \sin \alpha' \cos (\alpha' + \phi) \cos (2\alpha' - 2\theta + \phi) \\ & = \frac{c}{\gamma y} \cos \phi \cos (2\alpha' + \phi) \dots \dots \dots (4) \end{aligned}$$

where γ is the unit weight of the soil. Résal concluded that this equation was not integrable.



(a) Location of element on hypothetical failure surface.



(b) Definition of element and stresses.

Figure 1.--Element definition for Résal's derivation.

In 1922, Frontard (1922) succeeded in solving equation 4 for the coordinates of the passive failure surface under the conditions of the Rankine-Résal stress assumptions. His solution was presented as follows:

$$x' = \frac{c \cos \phi \tan \theta (\lambda_0 \cos \theta + \cos \phi \sin \lambda_0 - \lambda \cos \theta - \cos \phi \sin \lambda)}{\gamma \sin (\theta - \phi) \sqrt{\sin (\theta - \phi) \sin (\theta + \phi)}} \dots \dots \dots (5a)$$

$$y' = \frac{c \cos \phi \tan \theta}{\gamma \sin (\theta - \phi) \sin (\theta + \phi)} \left[\frac{\sin \phi}{\tan \theta} - \sqrt{\sin (\theta - \phi) \sin (\theta + \phi)} \sin \lambda + \cos \theta \cos \lambda \right] \dots \dots \dots (5b)$$

where x' and y' are the coordinates in the directions parallel to the ground slope and vertically below ground slope, respectively.

The parameter λ is defined by the expression

$$\tan \frac{\lambda}{2} = \sqrt{\frac{\sin \theta + \sin \phi}{\sin \theta - \sin \phi}} \tan \left(\alpha' - \frac{\theta - \phi}{2} \right) \dots \dots \dots (6a)$$

Corresponding to the coordinates $x' = y' = 0$, the angle $\alpha' = \pi/4 - \phi/2$ in the passive case and accordingly, the parameter λ_0 is defined by the expression

$$\tan \frac{\lambda_0}{2} = \sqrt{\frac{\sin \theta + \sin \phi}{\sin \theta - \sin \phi}} \tan \left(\frac{\pi}{4} - \frac{\theta}{2} \right) \dots \dots \dots (6b)$$

By using Frontard's approach, similar expressions can be derived for the active failure surface. They are as follows:

$$x' = \frac{c \cos \phi \tan \theta (\lambda_0 \cos \theta + \cos \phi \sin \lambda_0 - \lambda \cos \theta - \cos \phi \sin \lambda)}{\gamma \sin (\theta - \phi) \sqrt{\sin (\theta - \phi) \sin (\theta + \phi)}} \dots \dots \dots (7a)$$

$$y' = \frac{c \cos \phi \tan \theta}{\gamma \sin (\theta - \phi) \sin (\theta + \phi)} \left[\frac{\sin \phi}{\tan \theta} + \sqrt{\sin (\theta - \phi) \sin (\theta + \phi)} \sin \lambda + \cos \theta \cos \lambda \right] \dots \dots \dots (7b)$$

$$\tan \frac{\lambda}{2} = \sqrt{\frac{\sin \theta + \sin \phi}{\sin \theta - \sin \phi}} \tan \left(\alpha' + \frac{\theta - \phi}{2} \right) \dots \dots \dots (8a)$$

$$\tan \frac{\lambda_0}{2} = \sqrt{\frac{\sin \theta + \sin \phi}{\sin \theta - \sin \phi}} \tan \left(\frac{\pi}{4} + \frac{\theta}{2} \right) \dots \dots \dots (8b)$$

In 1936, Terzaghi (1936) presented a discussion of Frontard's solution in connection with the analysis of simple slopes. He implied that Frontard had combined the vertical projections of the active and passive failure surfaces to obtain the critical height of simple slopes. However, Frontard made no statements in his 1922 paper with regard to the application of his work to simple slopes; nor, indeed, did he mention the active failure surface or present the solution for same.

Terzaghi correctly criticized attempts to combine the active and passive curves obtained by this procedure for, by the assumptions of the infinite slope theory, the active and passive states of stress cannot exist simultaneously in a slope. However, he was incorrect in attributing any statements to Frontard regarding the applicability of this theory to real slopes.

Hartsog and Martin (1974) presented general solutions for the active and passive earth pressures in an infinite slope for cases with and without seepage forces. They used the Mohr stress coordinates as a basis for their work, and derived expressions for the state of stress on a plane oriented at any angle under conditions of either active or passive failure. Their paper formed the basis for the following development.

The active and passive stress circles for the general case of a point located beneath the phreatic surface when ground water flows parallel to the ground slope are shown in figure 2. Note that $\bar{\sigma}_a$ and τ_a are the effective normal and shear stresses, respectively, acting on a plane parallel to ground surface at the point or depth being considered. For a depth less than that to ground water, the coordinates $(\bar{\sigma}_a, \tau_a)$ would simply lie along the line extending from the origin of stresses at an angle, θ , to the $\bar{\sigma}$, or normal stress, axis.

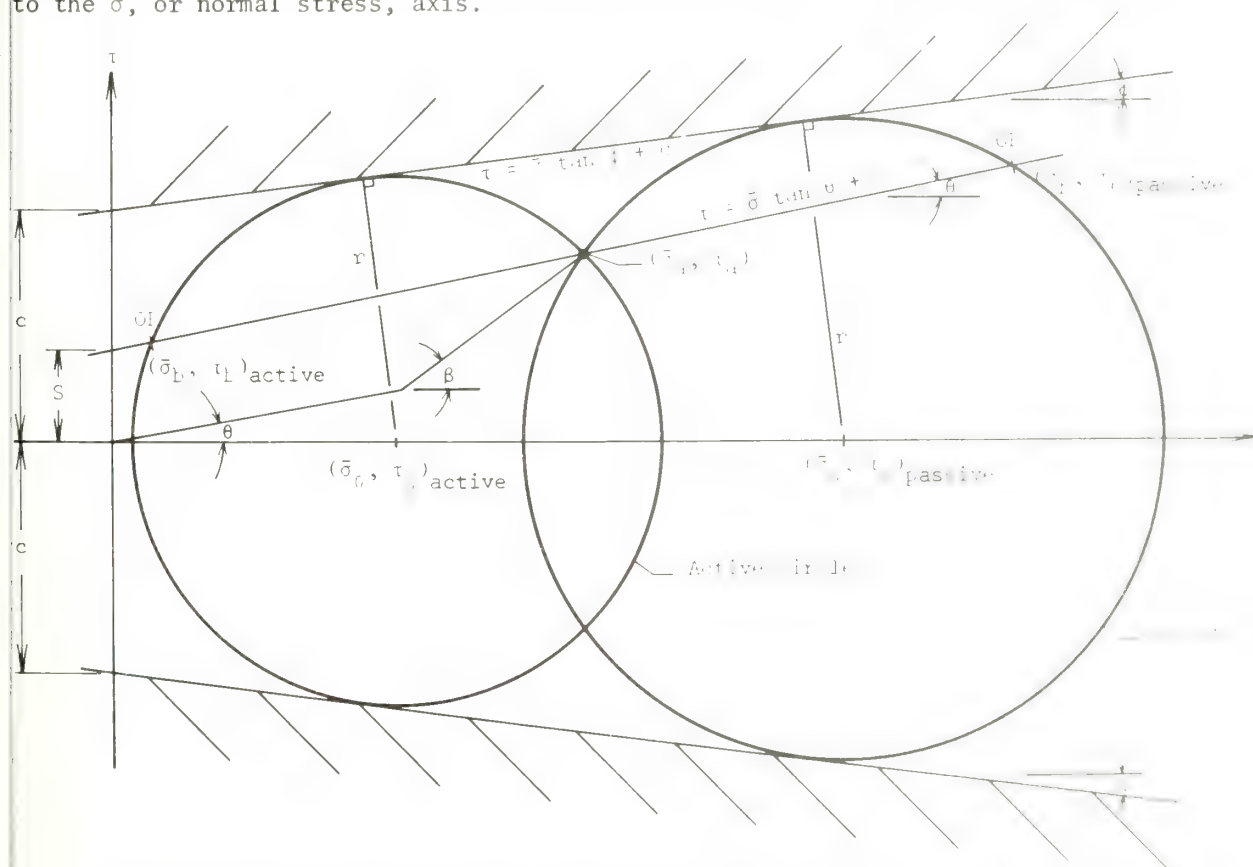


Figure 2.--Active and passive stress circles and their relationship to Mohr's rupture envelope. {After Hartsog and Martin (2)}.

The angle, β , shown in figure 2, can be expressed as

$$\beta = \tan^{-1} \left[\left(1 + \frac{\gamma_w}{\gamma_b} \right) \tan \theta \right] \dots \dots \dots (9)$$

and the seepage force per unit area, S , is given by

$$S = \gamma_w \sin \theta (z - z_w) \cos \theta \dots \dots \dots (10)$$

where z is the vertical depth below ground surface to the point being considered, z_w is the vertical depth below ground surface to the phreatic surface, and γ_w is the unit weight of water.

By defining the angle, α , as shown in figure 3, Hartsog and Martin derived the following general expressions for the stresses $\bar{\sigma}_c$ and τ_c on a plane oriented at any angle, α , at depth z :

$$\bar{\sigma}_c = \frac{2 \bar{\sigma}_0 + \bar{\sigma}_b (-1 + \tan^2 \alpha - 2 \tan \alpha \tan \theta) - 2 S \tan \alpha}{1 + \tan^2 \alpha} \dots \dots \dots (11)$$

$$\tau_c = \tau_b + (\bar{\sigma}_c - \bar{\sigma}_b) \tan \alpha \dots \dots \dots (12)$$

where

$$\bar{\sigma}_b = \frac{2 \bar{\sigma}_0 - 2 S \tan \theta}{(1 + \tan^2 \theta)} - \bar{\sigma}_a \dots \dots \dots (13)$$

$$\tau_b = \bar{\sigma}_b \tan \theta + S \dots \dots \dots (14)$$

$$\bar{\sigma}_a = \gamma_t z_w \cos^2 \theta + \gamma_b (z - z_w) \cos^2 \theta \dots \dots \dots (15)$$

$$\begin{aligned} \bar{\sigma}_0 = & \bar{\sigma}_a (1 + \tan^2 \phi) + c \tan \phi \\ & \pm \{ [- \bar{\sigma}_a (1 + \tan^2 \phi) - c \tan \phi]^2 \\ & - [\bar{\sigma}_a^2 (1 + \tan^2 \phi + \tan^2 \theta + \tan^2 \phi \tan^2 \theta) \\ & + 2 \bar{\sigma}_a S \tan \theta (1 + \tan^2 \phi) \\ & + S^2 (1 + \tan^2 \phi) - c^2] \}^{\frac{1}{2}} \dots \dots \dots (16) \end{aligned}$$

In the above expressions, γ_t is the unit weight of the soil above ground water level and γ_b is the buoyant unit weight of the soil below ground water level. The (+) and (-) signs in equation 16 correspond to the passive and active stress circles, respectively.

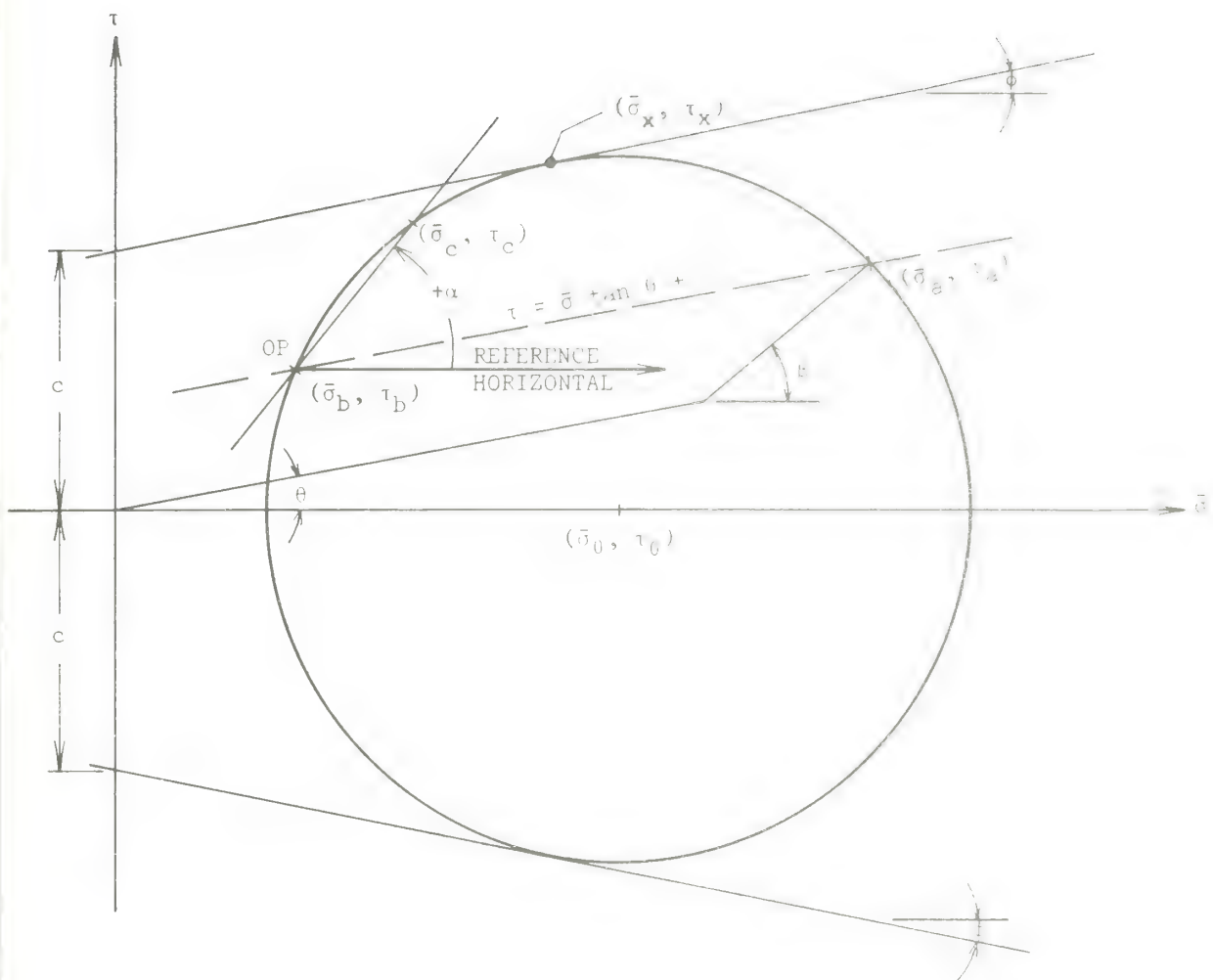


Figure 3.--Typical stress circle. {After Hartsog and Martin (2)}.

GENERAL SOLUTION

In figure 3, the point of tangency of the stress circle with the strength envelope is defined by the coordinates $(\bar{\sigma}_x, \tau_x)$. The tangent of the angle, α_f , of the line connecting the origin of planes (OP) and the point of tangency can be expressed as

$$m = \tan \alpha_f = \frac{\tau_x - \tau_b}{\bar{\sigma}_x - \bar{\sigma}_b} \dots \dots \dots (17)$$

It can be shown that

$$\bar{\sigma}_x = \frac{\bar{\sigma}_0 - c \tan \phi}{1 + \tan^2 \phi} \dots \dots \dots (18)$$

and

$$\tau_x = \left(\frac{\bar{\sigma}_0 - c \tan \phi}{1 + \tan^2 \phi} \right) \tan \phi + c \dots \dots \dots (19)$$

Combining equations 13, 14, 18, and 19, the expression for m can be written:

$$\begin{aligned} & \bar{\sigma}_0 [\tan \phi (1 + \tan^2 \theta) - 2 \tan \theta (1 + \tan^2 \phi)] \\ & + \bar{\sigma}_a [\tan \theta (1 + \tan^2 \phi) (1 + \tan^2 \theta)] \\ & + c [(1 + \tan^2 \phi) (1 + \tan^2 \theta) \\ & \quad - \tan^2 \phi (1 + \tan^2 \theta)] \\ & + S [2 \tan^2 \theta (1 + \tan^2 \phi) \\ & \quad - (1 + \tan^2 \phi) (1 + \tan^2 \theta)] \\ m = & \frac{\bar{\sigma}_0 [(1 + \tan^2 \theta) - 2 (1 + \tan^2 \phi)] \\ & + \bar{\sigma}_a [(1 + \tan^2 \phi) (1 + \tan^2 \theta)] \\ & - c [\tan \phi (1 + \tan^2 \theta)] \\ & + S [2 \tan \theta (1 + \tan^2 \phi)] \dots \dots \dots (20) \end{aligned}$$

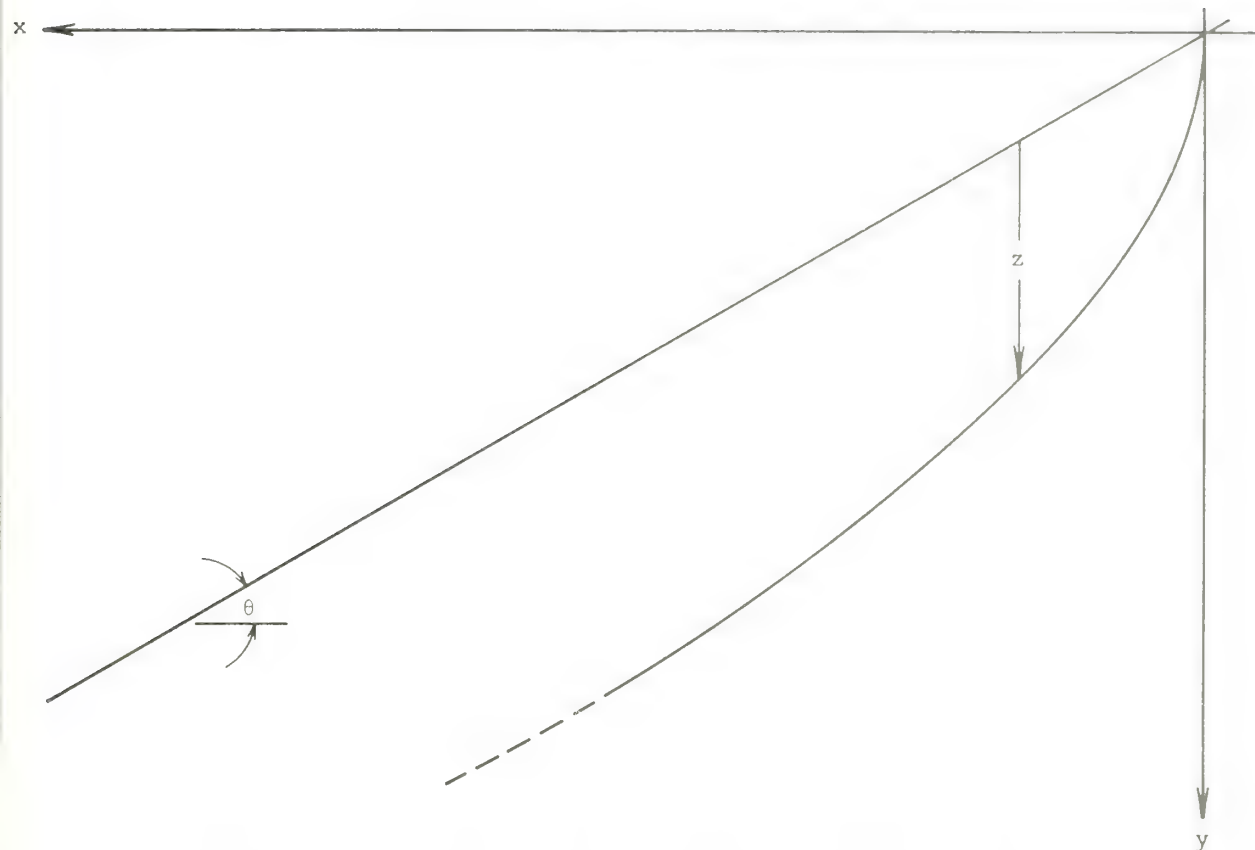


Figure 4.--Coordinate system (hypothetical failure surface).

It is convenient to express the equation for the failure surface in terms of rectangular coordinates. Considering the hypothetical failure surface shown in Figure 4 and choosing the coordinates $x = y = 0$ to denote the intersection of the failure surface with the ground surface, the equation for the failure surface can be written

$$y = z + x \tan \theta \quad \dots \dots \dots (21)$$

The slope of the failure surface is given by the expression

$$m = \frac{dy}{dx} \quad \dots \dots \dots (22)$$

Taking the derivative of the equation for the failure surface, equation 21, the expression for x is obtained as follows:

$$m = \frac{dy}{dx} = \frac{dz}{dx} + \tan \theta \quad \dots \dots \dots (23)$$

and

$$x = \int_0^x dx = \int_0^z \left(\frac{1}{m - \tan \theta} \right) dz \quad \dots \dots \dots (24)$$

Combining equations 10, 15, 16, and 20, it can be shown that, for the general case where the point being considered lies below the phreatic surface,

$$\begin{aligned} \frac{1}{m - \tan \theta} &= \frac{-(\tan \theta + \tan \phi)}{(1 + \tan^2 \theta)} \\ &\cos^2 \theta \{ (z - z_w) [\gamma_b (\tan \theta + \tan \phi) \\ &\quad + \gamma_w \tan \theta] \\ &\quad + z_w \gamma_t (\tan \theta + \tan \phi) \\ &\quad + \frac{+ c (1 + \tan^2 \theta)^{\frac{1}{2}}}{\cos \phi \{ (z - z_w) [\gamma_b (\tan \phi - \tan \theta) \\ &\quad - \gamma_w \tan \theta] \\ &\quad + z_w \gamma_t (\tan \phi - \tan \theta) \\ &\quad + c (1 + \tan^2 \theta)^{\frac{1}{2}} \} \dots \dots \dots (25) \end{aligned}$$

Similarly, for a point above the ground water level, or for the special case of no seepage,

$$\begin{aligned} \frac{1}{m - \tan \theta} &= \frac{-(\tan \theta + \tan \phi)}{(1 + \tan^2 \theta)} \\ &\cos^2 \theta \{ z \gamma_t (\tan \theta + \tan \phi) \\ &\quad + \frac{+ c (1 + \tan^2 \theta)^{\frac{1}{2}}}{\cos \phi \{ z \gamma_t (\tan \phi - \tan \theta) \\ &\quad + c (1 + \tan^2 \theta)^{\frac{1}{2}} \} \dots \dots \dots (26) \end{aligned}$$

where, in each case, the (-) and (+) signs correspond to the passive and active situations, respectively.

Thus, from equations 24 and 25, for $z \geq z_w$,

$$\begin{aligned} x - x_0 &= A (\eta - \eta_0) \mp [B \frac{\sqrt{uv}}{b} \\ &\quad - \frac{Bk}{b \sqrt{-bb'}} \tan^{-1} \left(\frac{\sqrt{-bb' + uv}}{bv} \right)] \dots \dots \dots (27) \end{aligned}$$

where $\eta = z - z_w$, and η_0 and x_0 correspond to the depth $z = z_w$. Again, the (-) and (+) signs correspond to the passive and active cases, respectively, and the remaining parameters and variables are defined as follows:

$$A = \frac{- (\tan \theta + \tan \phi)}{(1 + \tan^2 \theta)} \quad (28a)$$

$$B = \cos^2 \theta (1 + \tan^2 \phi)^{\frac{1}{2}} \quad (28b)$$

$$a = z_w \gamma_t (\tan \phi - \tan \theta) + c (1 + \tan^2 \theta) \quad (28c)$$

$$b = \gamma_b (\tan \phi - \tan \theta) - \gamma_w \tan \theta \quad (28d)$$

$$a' = z_w \gamma_t (\tan \theta + \tan \phi) + c (1 + \tan^2 \theta) \quad (28e)$$

$$b' = \gamma_b (\tan \theta + \tan \phi) + \gamma_w \tan \theta \quad (28f)$$

$$u = a + b n \quad (28g)$$

$$v = a' + b' n \quad (28h)$$

$$k = a b' - a' b \quad (29g)$$

Likewise, from equations 24 and 26, for $z \leq z_w$ (or for the case of no seepage),

$$x - x_0 = A (z - z_0) + \left[B \frac{\sqrt{uv}}{b} - \frac{Bk}{b \sqrt{-bb'}} \tan^{-1} \left(\frac{\sqrt{-bb' - uv}}{bv} \right) \right] z_0 \quad (30)$$

where x_0 and z_0 correspond to ground surface (i.e., $x_0 = z_0 = 0$) and the (-) and (+) signs correspond to the passive and active cases, respectively. Here A and B are as defined in equation 28, and the remaining parameters and variables are defined as follows:

$$a = c (1 + \tan^2 \theta) \quad (31a)$$

$$b = \gamma_t (\tan \phi - \tan \theta) \quad (31b)$$

$$a' = a = c (1 + \tan^2 \theta) \quad (31c)$$

$$b' = \gamma_t (\tan \theta + \tan \phi) \quad (31d)$$

$$u = a + b z \quad (31e)$$

$$v = a' + b' z \quad (31f)$$

$$k = a b' - a' b \quad (31g)$$

Equation 30 can be shown to agree with the solutions obtained using Frontard's approach.

Note that the above solutions are limited to situations where $c > 0$ and

$\theta > \tan^{-1} \left[\frac{\gamma_b}{\gamma_{sat}} \tan \phi \right]$, where γ_{sat} is the saturated unit weight of soil below the water table ($\gamma_{sat} = \gamma_b + \gamma_w$). For the case of no seepage, the above solutions are limited to situations where $\theta > \phi$. For conditions other than these, special (and generally simpler) solutions can be found.

RESULTS

Representative failure curves obtained from equations 27 and 30 are shown in figure 5. For the particular slope and soil properties chosen for illustrative purposes in figure 5, the critical depth for the case of no seepage is 11.85 ft. The curves for two of the cases, $z_w = 5$ ft. and $z_w > 11.85$ ft., coincide to a depth of 5 ft.

The critical depths z_1 , z_2 , and z_3 are found from the expressions

$$z_1 = \frac{c}{\cos^2 \theta \{ \gamma_b (\tan \theta - \tan \phi) + \gamma_w \tan \theta \}} \dots \dots \dots (32)$$

$$z_2 = z_w + \frac{c - z_w \gamma_t \cos^2 \theta (\tan \theta - \tan \phi)}{\cos^2 \theta \{ \gamma_b (\tan \theta - \tan \phi) + \gamma_w \tan \theta \}} \dots \dots \dots (33)$$

$$z_3 = \frac{c}{\gamma_t \cos^2 \theta (\tan \theta - \tan \phi)} \dots \dots \dots (34)$$

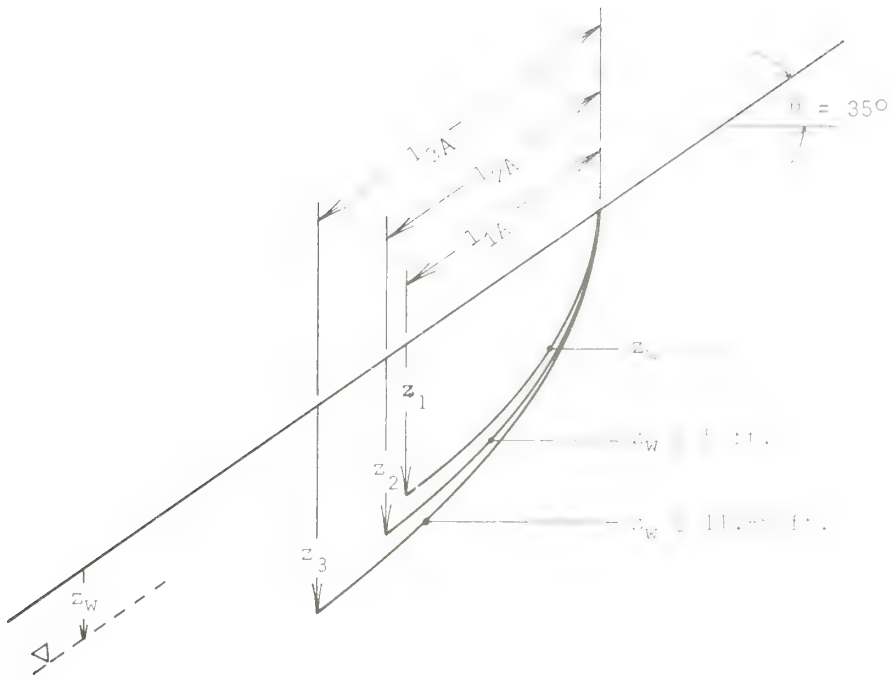
The values of l_{1A} , l_{1P} , l_{2A} , l_{2P} , l_{3A} , and l_{3P} are found by dividing the appropriate horizontal lengths, x , by $\cos \theta$.

The ratios l_{3A}/z_3 , and l_{3P}/z_3 are plotted in figures 6a and 6b to illustrate their dependency upon ϕ and θ . For cases of no seepage, the length-to-depth ratios are independent of the soil properties, c and γ_t . Auxiliary curves have been plotted in figures 6a and 6b to illustrate the dependence of length-to-depth ratios on the values of $(\theta - \phi)$. As $(\theta - \phi)$ approaches zero, the length-to-depth ratios increase toward infinity.

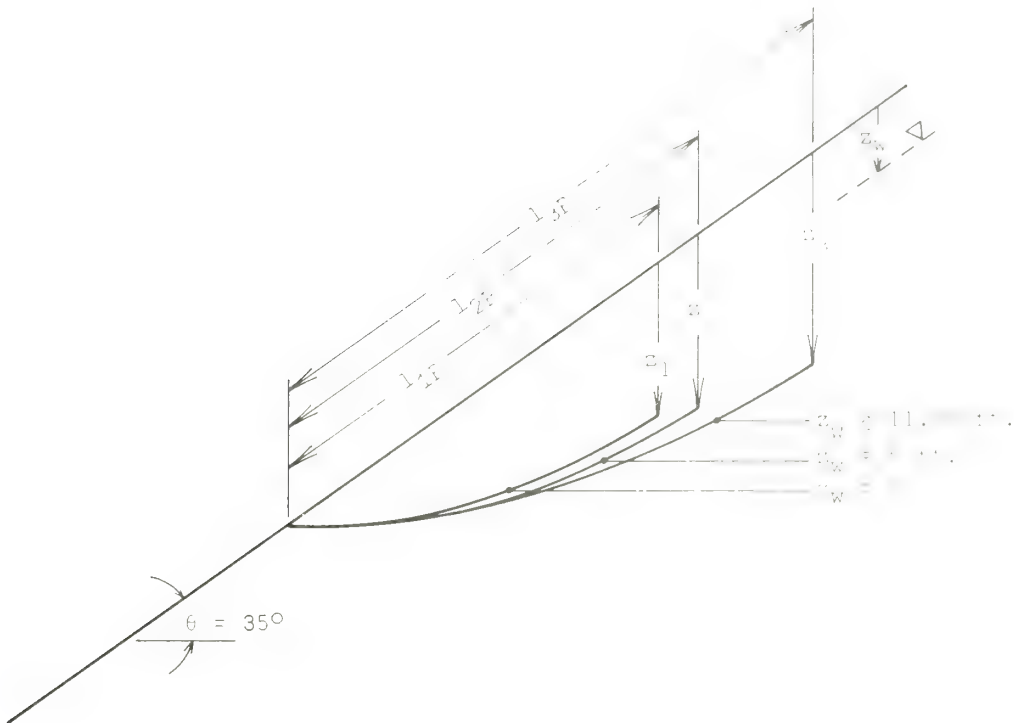
The length-to-depth ratios depend upon the buoyant unit weight of the soil, γ_b , as well as upon ϕ and θ for cases where seepage occurs throughout the soil profile and flow is parallel to ground slope. The relationships of l_{1A}/z_1 and l_{1P}/z_1 to ϕ and θ for buoyant unit weights of 30, 60, and 90 p.c.f. are shown in figures 7, 8, and 9, respectively. As in the case of no seepage, these length-to-depth ratios are independent of soil cohesive strength, c .

Although not illustrated in figures 7, 8, and 9, the length-to-depth ratios increase rapidly toward infinity as the values of $\tan \theta - \frac{\gamma_b}{\gamma_{sat}} \tan \phi$ approach zero.

Finally, it is of interest to examine the variations of length-to-depth ratios as z_w varies between 0 and z_3 . Figure 10 shows the relationships of l_{2A}/z_2 , l_{2P}/z_2 , and $(l_{2A} + l_{2P})/z_2$ to z_w for the particular slope and soil conditions assumed in figure 5. The actual variations of lengths l_{2A} , l_{2P} , and $(l_{2A} + l_{2P})$ with z_w are also shown in figure 10.



(a) Active curves



(b) Passive curves

Figure 5.--Failure curves for infinite slope with water table at various depths.
 (Assumed soil properties: $c = 500$ p.s.f., $\phi = 10^\circ$, $\gamma_t = 120$ p.c.f.,
 $\gamma_b = 80$ p.c.f. Critical depths: $z_1 = 8.70$ ft., $z_2 = 11.00$ ft., $z_3 = 11.00$ ft.)

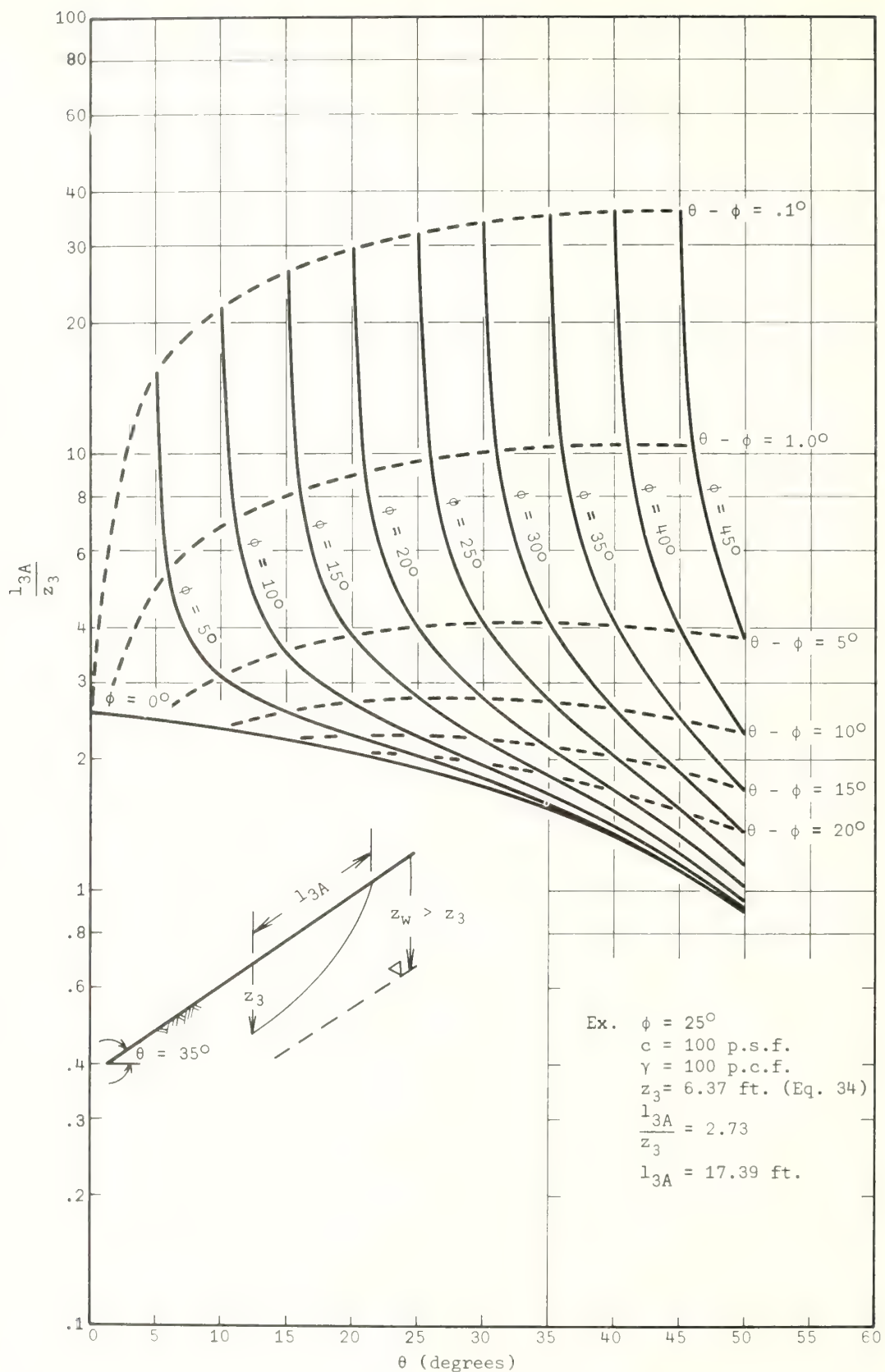


Figure 6a.--Length-to-depth ratios for cases of no seepage, active curves (i.e., $z_w >$ "dry" critical depth).

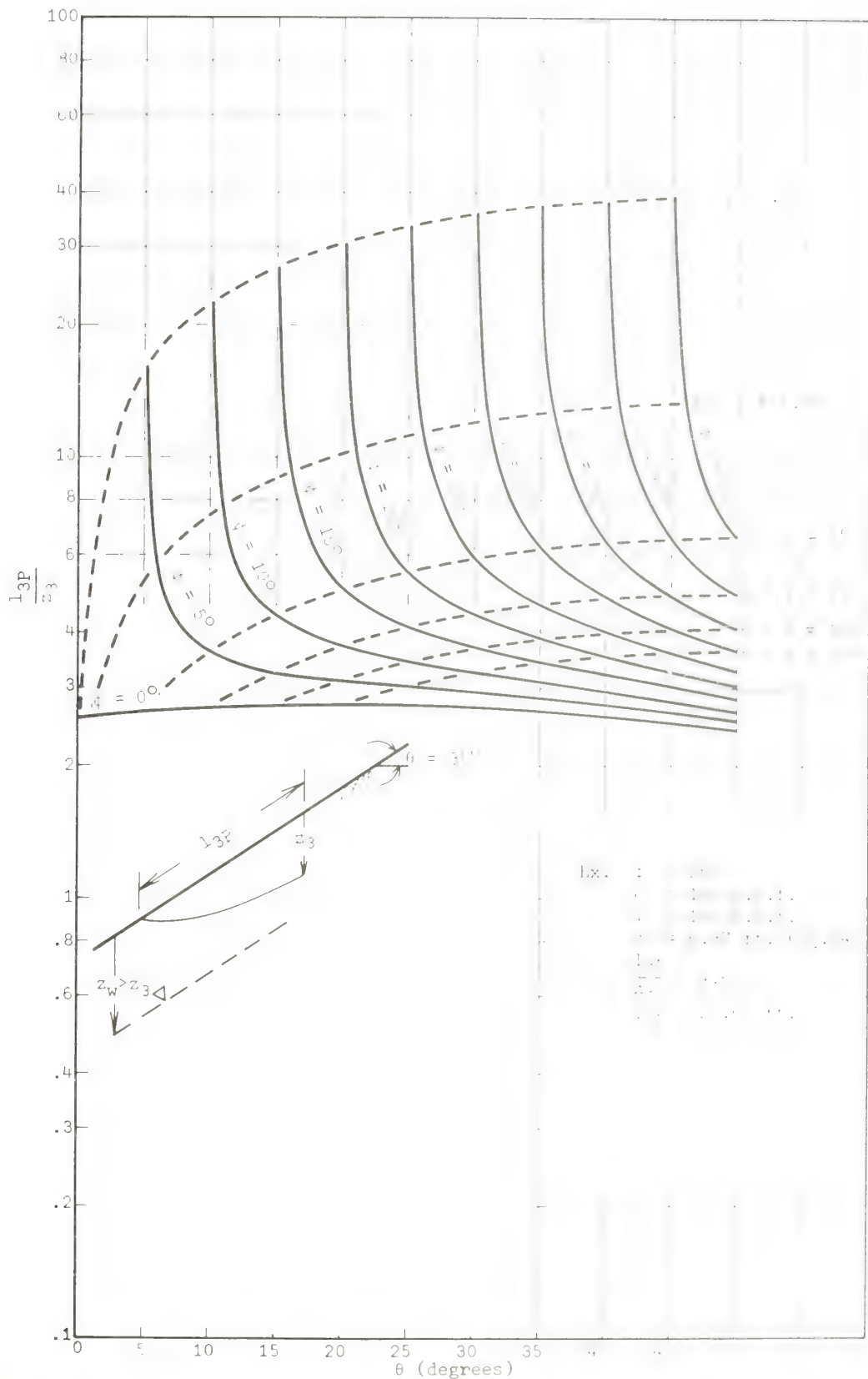


Figure 6b.--Length-to-depth ratio for angle θ (i.e., $z_w > z_3$) initial state.

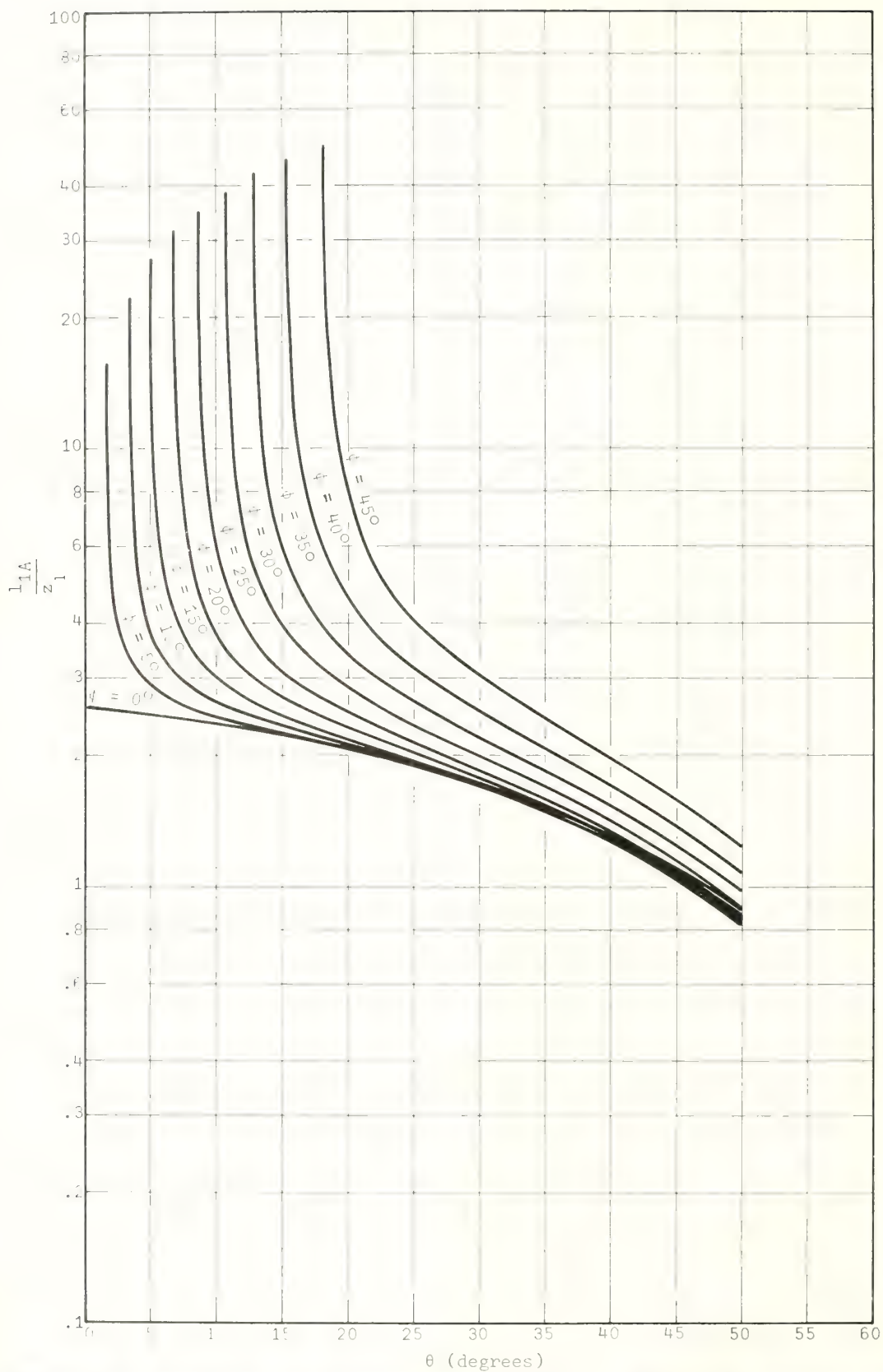


Figure 7a.--Length-to-depth ratios for $z_w = 0$, $\gamma_p = 30$ p.c.f., active curves.

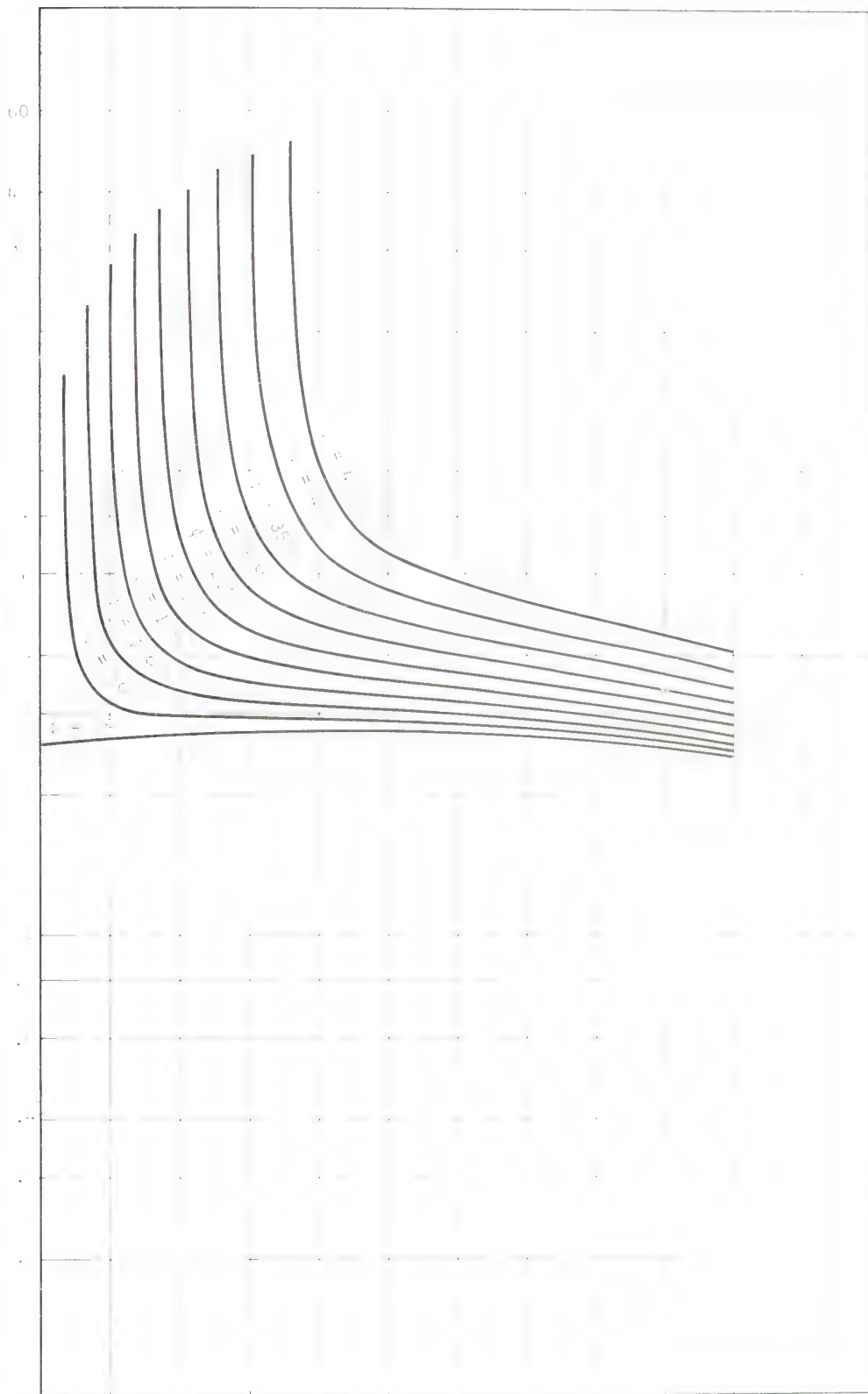


Figure 1. -- $\rho(x, y) = \rho = \text{const}$ and $\rho(x, y) = \rho_0 = 0.1, 0.2, 0.3, 0.35, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9$.

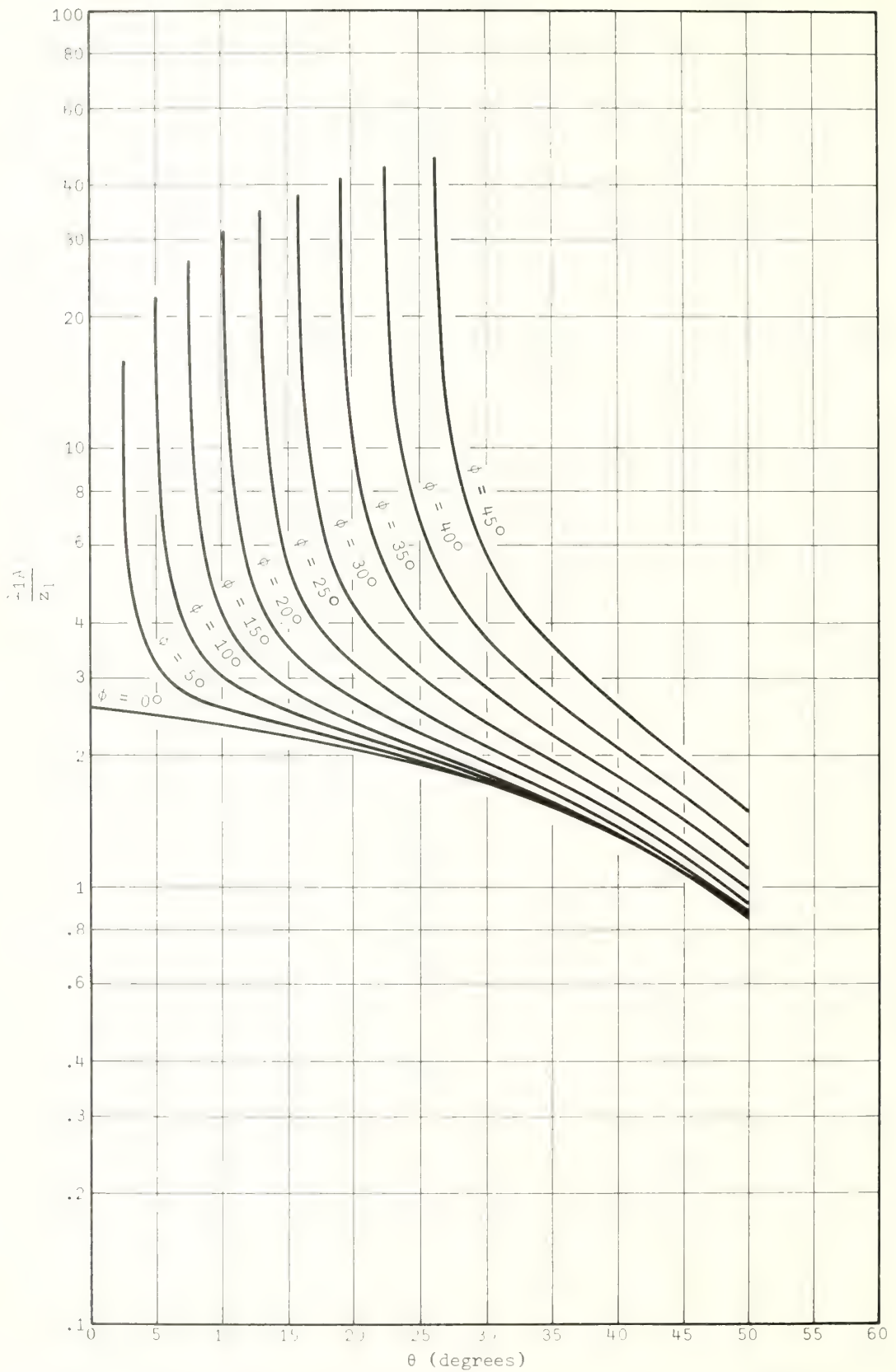


Figure 8a.--Length-to-depth ratios for $z_w = 0$, $\gamma_b = 60$ p.c.f., active curves.

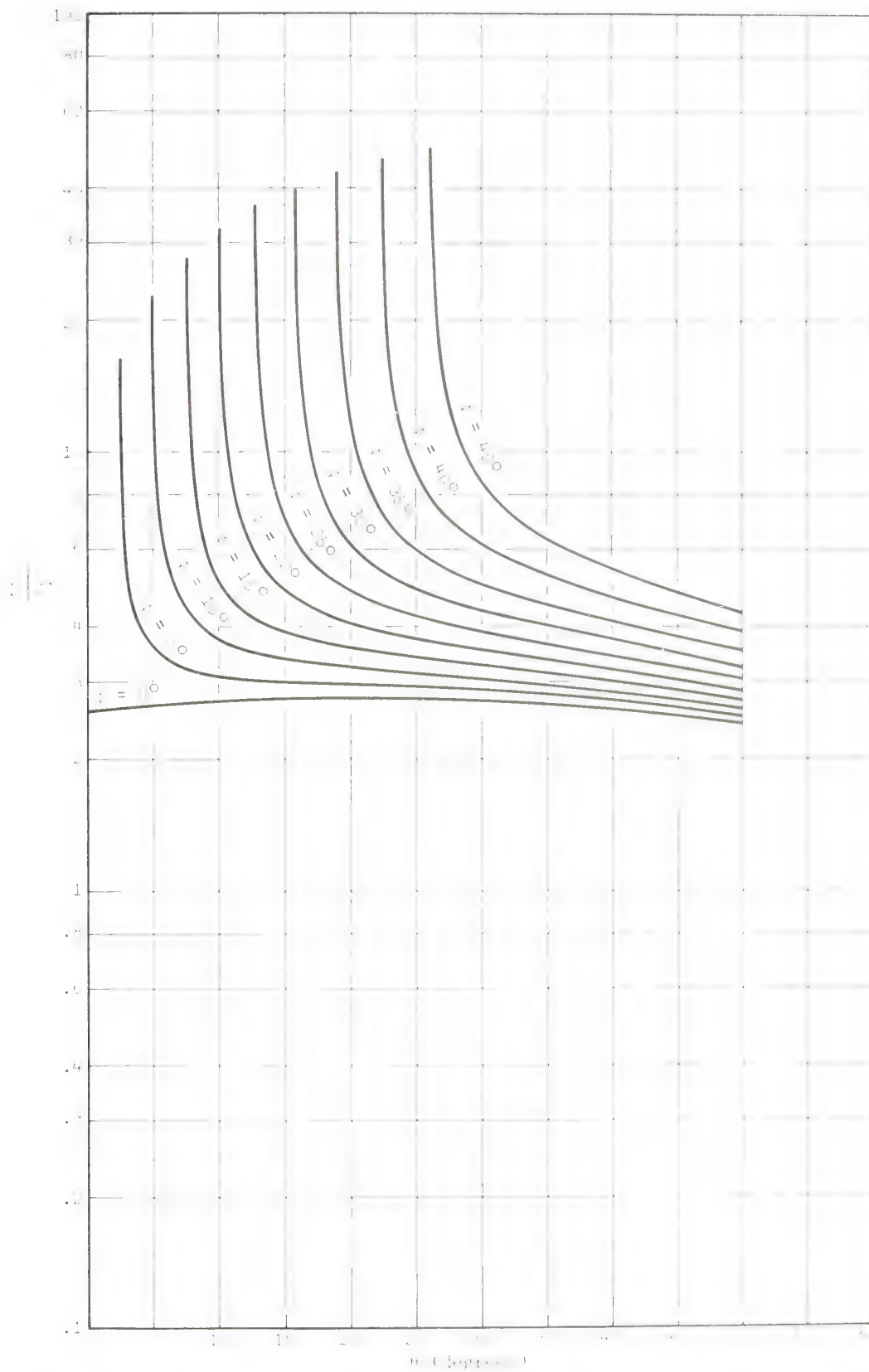


Figure 5b.--Length-to-depth ratios for $z_0 = 0, 100, 140, 180, 220, 260, 300, 340, 380, 420, 460$.

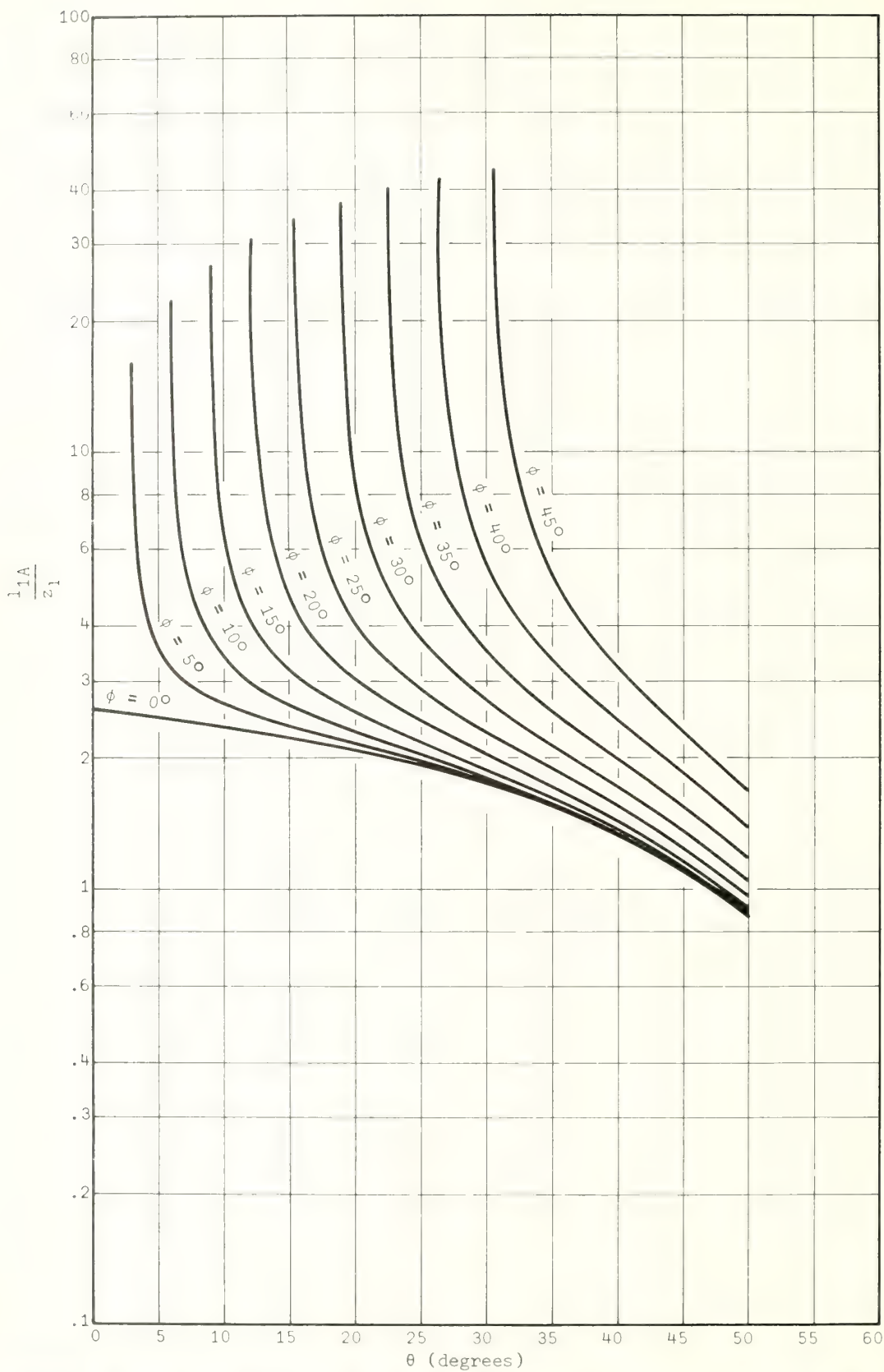


Figure 9a.--Length-to-depth ratios for $z_w = 0$, $\gamma_p = 90$ p.c.f., active curves.

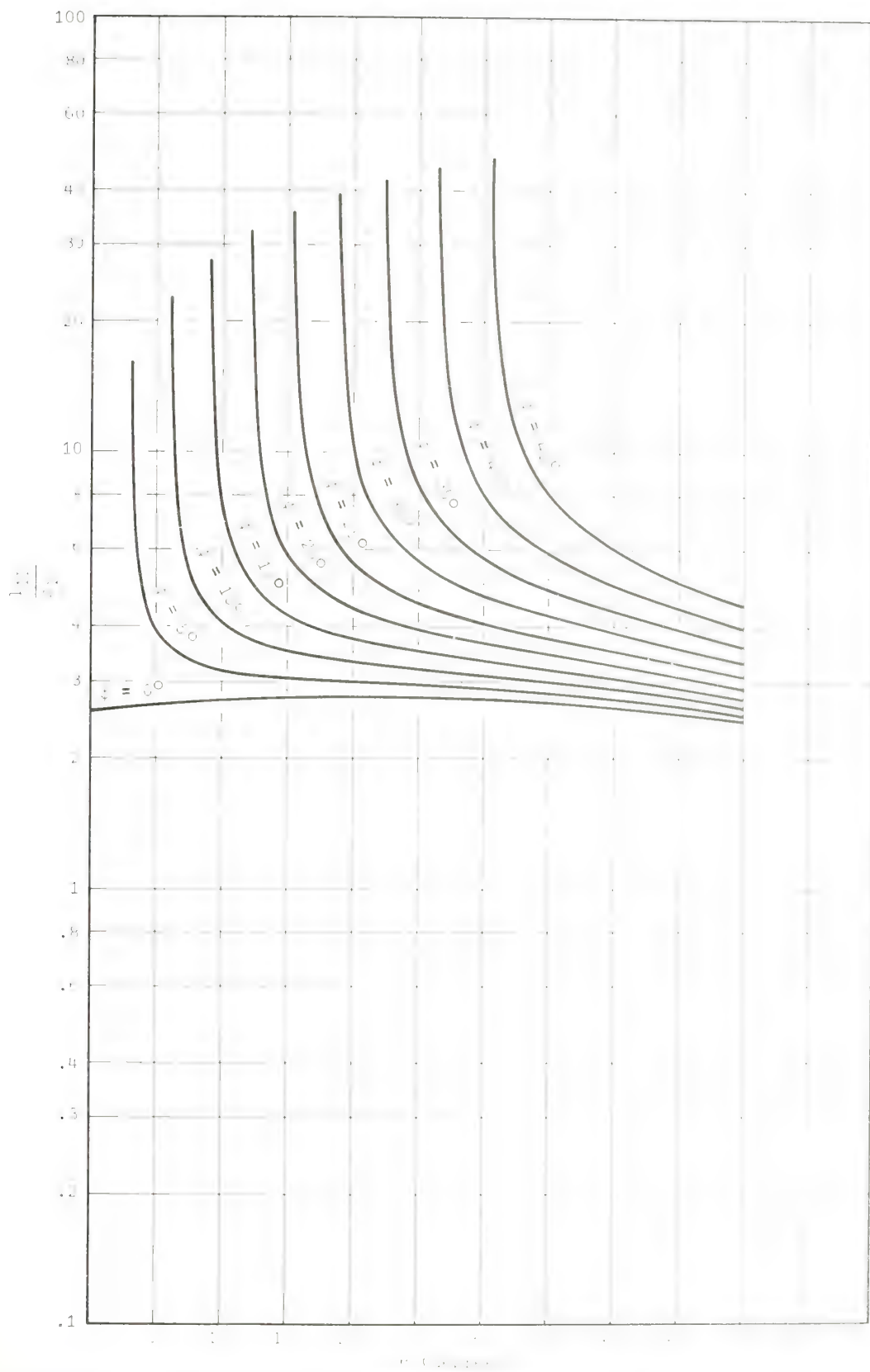


Figure 9b.--Length-to-depth ratios for $\sigma_0 = 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0$.

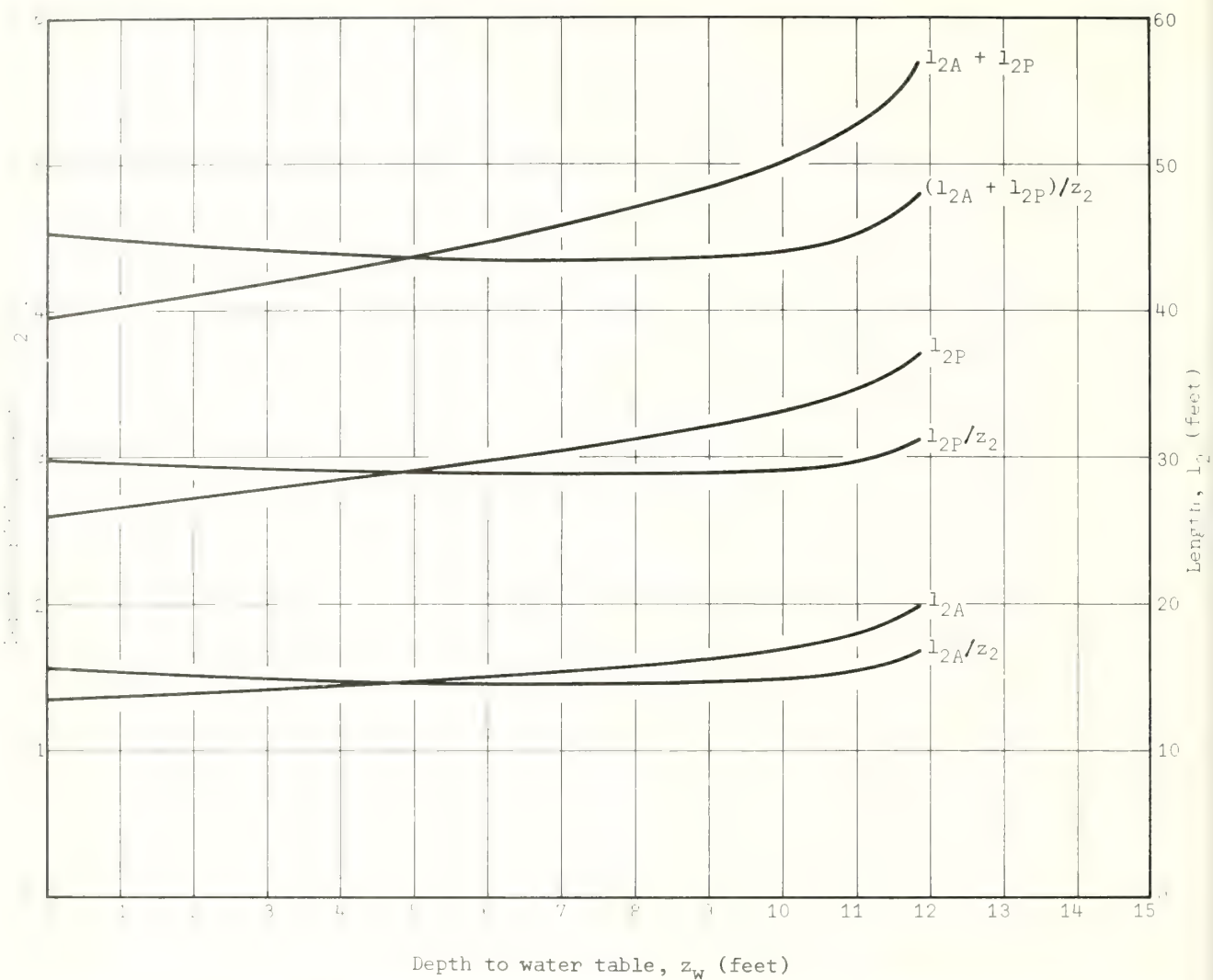


Figure 10.--Lengths and length-to-depth ratios versus z_w , for slope and soil conditions assumed in figure 5.

DISCUSSION

The results presented in figures 6a and 6b indicate that the combined active and passive length-to-critical depth ratios for cases of no seepage are less than 25 when $\theta - \phi > 1^\circ$ and $\phi < 45^\circ$. Figures 7, 8, and 9 illustrate that seepage reduces the length-to-depth ratios. Figures 5 and 10 illustrate that seepage reduces both the lengths of the failure surfaces and the critical depths. However, the minimum length-to-depth ratios can occur at intermediate seepage conditions (i.e., when $0 < z_w < z_{cr}$).

Although the shapes of the derived failure surfaces appear similar to those observed in real circumstances (e.g., see fig. 5), these active and passive failure surfaces cannot simply be combined, as was correctly pointed out by Terzaghi. If, as stated by Taylor, the active and passive states must exist simultaneously at the upper and lower ends, respectively, of a real failure, then the infinite slope theory remains an unsatisfactory means for predicting the state of stress within any real slopes in which failure is impending.

Consider the stresses on planes normal to the slope. Figure 11 illustrates these stresses for both the active and passive conditions, for the soil and slope conditions assumed in figure 5, without seepage. Note that the active and passive stress states are identical at the critical depth. This represents the depth where σ_a and τ_a are on the strength envelope (see fig. 2); hence, only one circle of stress is possible on the Mohr diagram. Note also that these stress distributions are not linear, as was assumed by Terzaghi.

Because of moment equilibrium, the shear stresses on planes normal to the slope are identical for both the active and passive conditions as well as for all intermediate stress conditions; only the normal stresses differ (except at the critical depth). Letting n and s represent the coordinates normal and parallel to the slope, respectively, (fig. 11) then from equation 11,

$$\begin{aligned} \bar{\tau}_s &= \bar{\sigma}_n (1 + 2 \tan^2 \theta) + 2 c \tan \theta \\ &\pm \frac{2}{\cos \phi} \{ \bar{\sigma}_n (\tan \phi - \tan \theta) \\ &\quad + 2 \bar{\sigma}_n (c \tan \phi - S \tan \theta) + (c^2 - S^2) \}^{1/2} \dots (35) \end{aligned}$$

where the (+) and (-) signs are associated with the passive and active conditions, respectively.

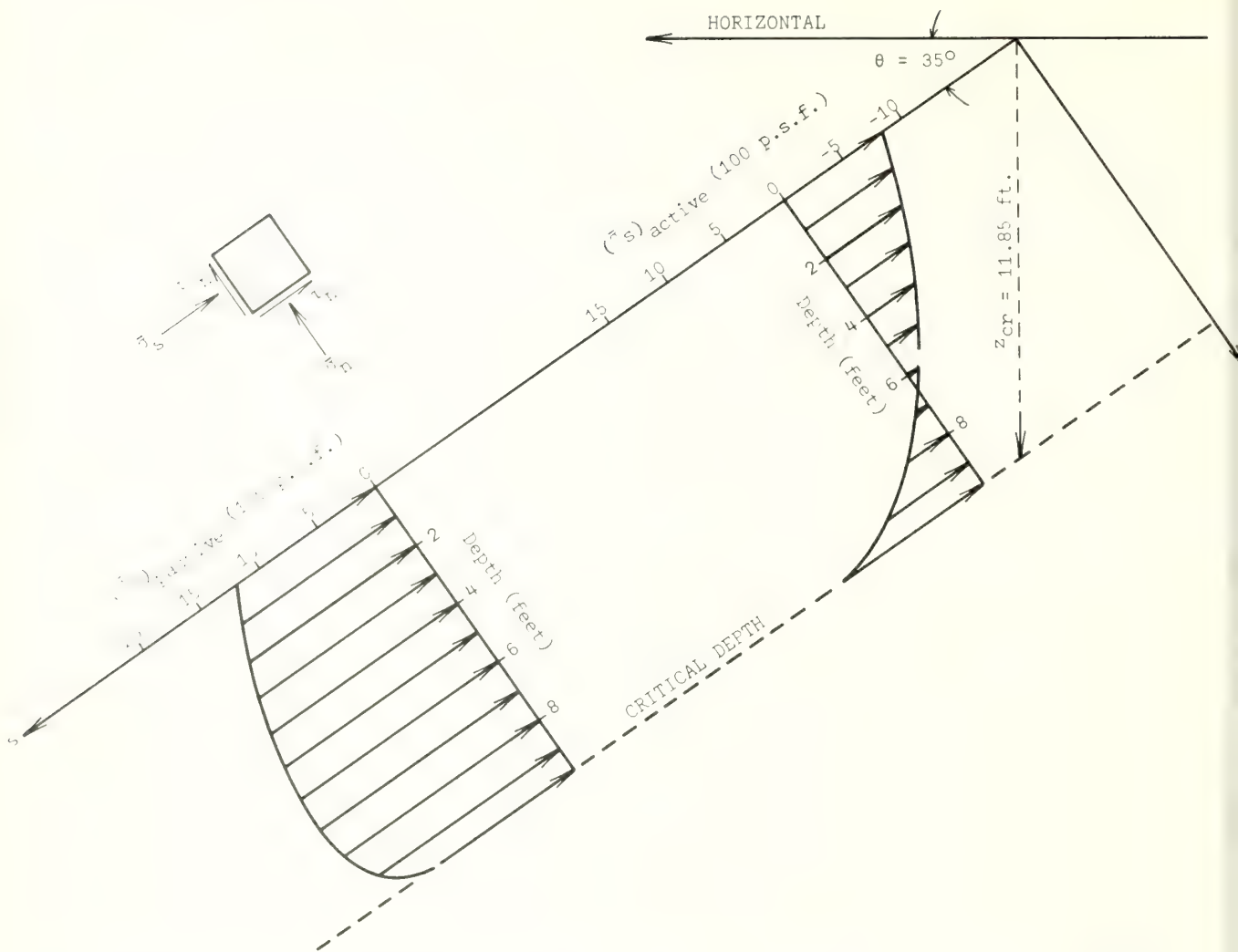


Figure 11.--Distribution of active and passive stresses on planes normal to ground slope under assumptions of the infinite slope theory ($\theta = 35^\circ$, $\phi = 10^\circ$, $c = 500$ p.s.f., $\gamma_t = 120$ p.c.f., $z_w > 11.85$ ft.).

It will be recalled from equation 10 that, in the case of seepage, S is the seepage force per unit area. However, it is convenient to consider S as simply an incremental shear stress which may be expressed

$$S = \tau_{ns} - \bar{\sigma}_n \tan \theta \quad \dots \dots \dots (36)$$

In cases without seepage, and under the assumptions of the infinite slope theory, $\tau_{ns} = \bar{\sigma}_n \tan \theta$, and therefore $S = 0$.

Combining equations 35 and 36,

$$\begin{aligned} \bar{\sigma}_s &= \bar{\sigma}_n (1 + 2 \tan^2 \phi) + 2 c \tan \phi \\ &\pm \frac{2}{\cos \phi} \{ (\bar{\sigma}_n \tan \phi + c)^2 - \tau_{ns}^2 \}^{\frac{1}{2}} \quad \dots \dots \dots (37) \end{aligned}$$

where, again, the (+) and (-) signs are associated with the passive and active conditions, respectively.

From equilibrium considerations,

$$\frac{\partial \tau_{ns}}{\partial n} = \gamma \sin \theta - \frac{\partial \bar{\sigma}_s}{\partial s} \quad \dots \dots \dots (38a)$$

$$\frac{\partial \bar{\sigma}_n}{\partial n} = \gamma \cos \theta - \frac{\partial \tau_{sn}}{\partial s} \quad \dots \dots \dots (38b)$$

$$\tau_{ns} = \tau_{sn} \quad \dots \dots \dots (38c)$$

Under the assumptions of the infinite slope theory, $\frac{\partial \bar{\sigma}_s}{\partial s} = \frac{\partial \tau_{sn}}{\partial s} = 0$, and the stresses within the slope are given simply as

$$\tau_{ns} = \tau_{sn} = \gamma n \sin \theta \quad \dots \dots \dots (39a)$$

$$\bar{\sigma}_n = \gamma n \cos \theta \quad \dots \dots \dots (39b)$$

$$\begin{aligned} & \bar{\sigma}_n (1 + 2 \tan^2 \phi) + 2 c \tan \phi \\ & - \frac{2}{\cos \phi} \{ (\bar{\sigma}_n \tan \phi + c)^2 - \tau_{ns}^2 \}^{1/2} \leq \bar{\sigma}_s \\ & \leq \bar{\sigma}_n (1 + 2 \tan^2 \phi) + 2 c \tan \phi \\ & + \frac{2}{\cos \phi} \{ (\bar{\sigma}_n \tan \phi + c)^2 - \tau_{ns}^2 \}^{1/2} \quad \dots \dots \dots (39c) \end{aligned}$$

where $\bar{\sigma}_s$ remains constant at all locations in the slope at a given depth.

However, if it is assumed that $\bar{\sigma}_s$ increases uniformly from the active to the passive condition in length of slope, L, then

$$\begin{aligned} \frac{\partial \bar{\sigma}_s}{\partial s} &= \frac{(\bar{\sigma}_s)_{\text{passive}} - (\bar{\sigma}_s)_{\text{active}}}{L} = \\ &= \frac{4}{L \cos \phi} \{ (\bar{\sigma}_n \tan \phi + c)^2 - \tau_{ns}^2 \}^{1/2} \quad \dots \dots \dots (40) \end{aligned}$$

whereby from equation 38a,

$$\frac{\partial \tau_{ns}}{\partial n} = \gamma \sin \theta - \frac{4}{L \cos \phi} \{ (\bar{\sigma}_n \tan \phi + c)^2 - \tau_{ns}^2 \}^{1/2} \quad \dots \dots \dots (41)$$

Assuming $\frac{\partial \tau_{sn}}{\partial s} = 0$, as in the infinite slope theory, then $\bar{\sigma}_n = \gamma_n \cos \theta$, and equation 41 becomes

$$\frac{d \tau_{ns}}{d n} = \gamma \sin \theta - \frac{4}{L \cos \phi} \{(\gamma n \cos \theta \tan \phi + c)^2 - \tau_{ns}^2\}^{\frac{1}{2}} \dots (42)$$

This provides a rational, though admittedly oversimplified and slightly inaccurate means for allowing the active and passive states of stress to occur simultaneously at the top and bottom ends, respectively, of a failure mass in a long slope. It is simplified in that the shear stresses on planes parallel and normal to the slope are constant for a given depth, as in the infinite slope theory; and in that the normal stresses on planes normal to the slope increase at a constant rate from the active to the passive values. It is inaccurate in that it does not enable development of the failure surfaces connecting the critical depth with ground surface at the ends of the failure mass. However, this inaccuracy should not be too serious if L is large relative to the lengths required to develop the connecting failure surfaces.

The effect of this modification of the infinite slope theory is to increase the critical depth. Unfortunately, attempts to solve equation 42 for τ_{ns} have been unsuccessful. However, a finite difference approximation has been programed to enable determination of the τ_{ns} versus depth relationship as well as the critical depth for any particular slope and soil.

Figure 12 illustrates the effects of varying L on the τ_{ns} vs. $\bar{\sigma}_n$ relationship and on the critical depth for the slope and soil conditions assumed in figure 5. No general conclusions can be drawn from figure 12 because it represents a particular case. However, the reader can easily conduct a similar analysis for any other slope and soil by programing a finite difference solution to the above differential equation. It will merely be noted that, for the slope and soil conditions assumed in figures 5 and 12, transition lengths less than about 100 times the critical depth of 11.85 ft. result in rapidly increasing modified critical depths.

It will be recalled from figure 5 that the critical depth is reduced from 11.85 to 8.7 ft., or about 25 percent, when $z_w = 0$, or seepage is occurring throughout the soil profile. However, according to figure 12, if the transition length was about 170 ft. (or approximately 14 times the conventional critical depth of 11.85 ft.), then the modified critical depth would be about 25 percent greater than the conventional critical depth. Thus, a depth of 11.85 ft. on a slope of this length (170 ft.) might be safe under a condition of seepage throughout the soil profile even though the conventional theory would predict an unsafe condition.

Discussion thus far has been limited to uniform, uninterrupted slopes. Usually, the major interest in natural slopes is with regard to their response to excavations, or cuts, and to such other activities as timber harvesting. Recent advances in the application of the finite element method of analysis seem to hold the greatest promise for assessing the response of natural slopes to such alterations. Nevertheless, it still remains necessary to be able to describe the state of stress within the slope before modification as well as the *in situ* material properties. Having done so, it may be possible to use the simple transition-length approach to assess the stability of many cut slopes.

Accuracy of any method of analysis remains limited by the ability to measure or predict stress history and soil characteristics. Further, more knowledge about seepage and pore pressures is needed, especially in the realm of unsaturated flow. Also, the mechanisms of creep and progressive failure require considerably more study and elucidation. It is apparent that any accurate, rational method of analysis will ultimately have to combine rheological and soil moisture characteristics with effective strength characteristics in order to fully account for the behavior of natural slopes.

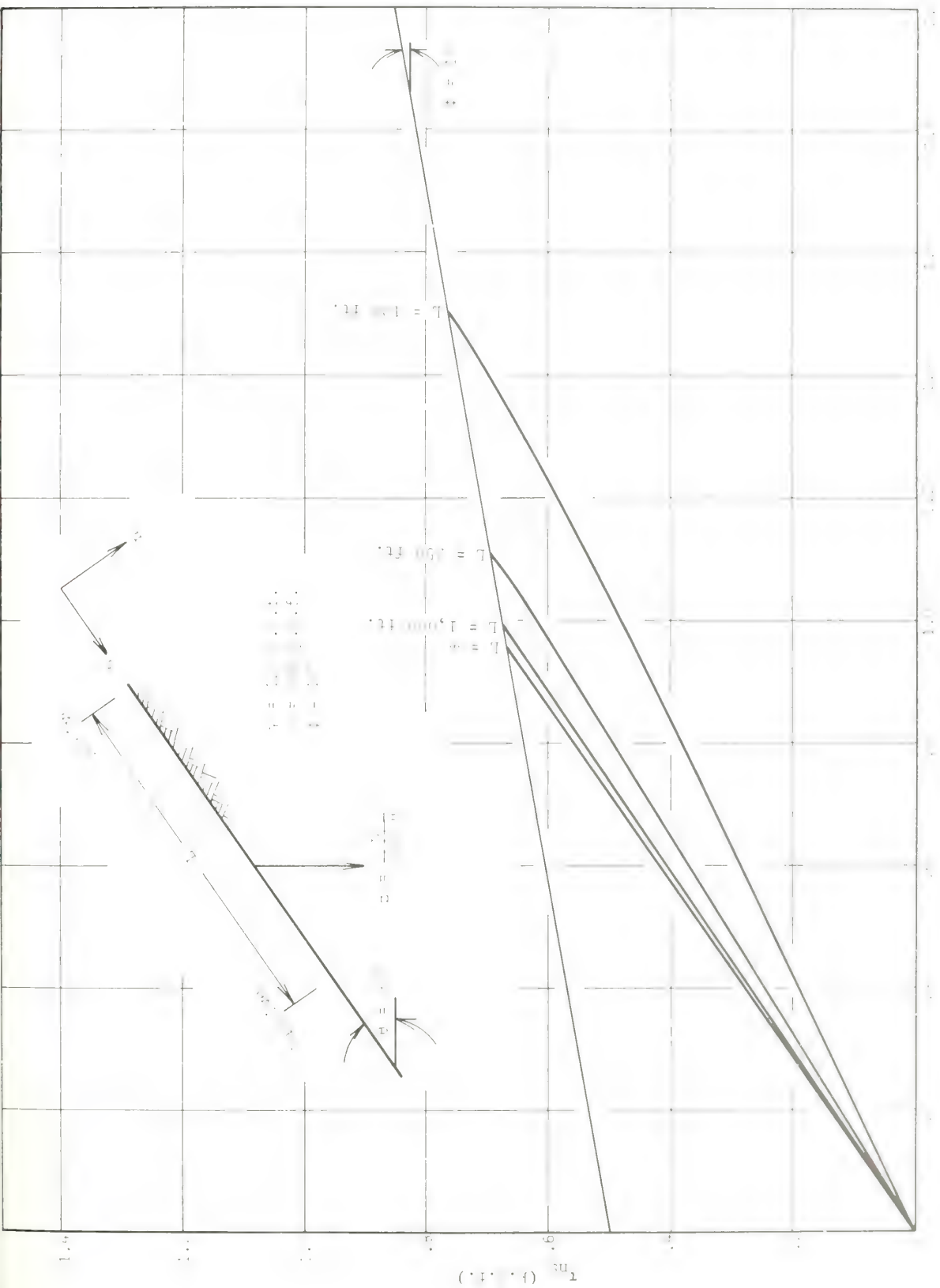


Figure 11. Graph of the relationship between the length of a cable and the horizontal distance between the points of suspension. The curves are for cable lengths of 1,000 ft., 2,500 ft., and ∞ .

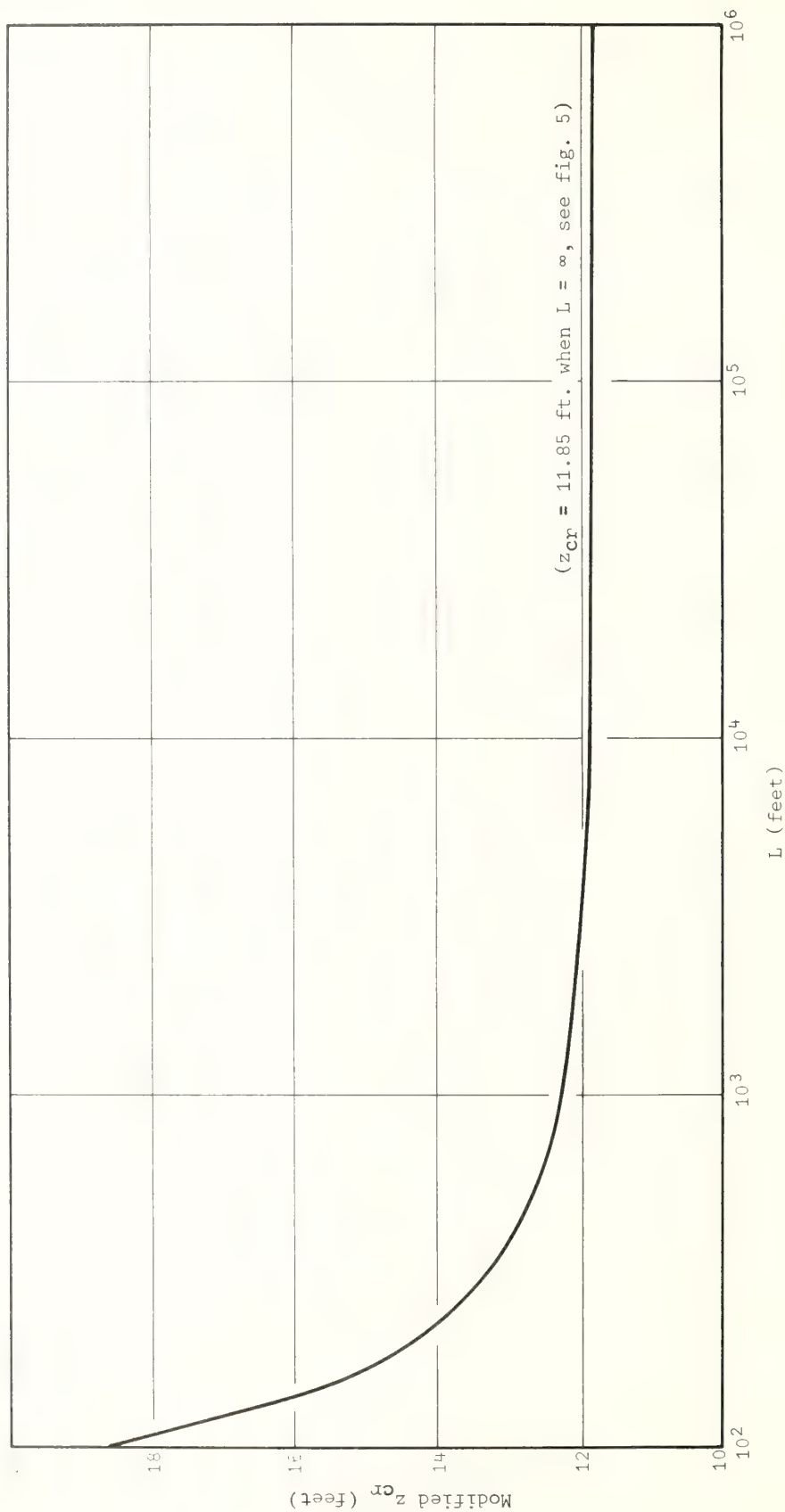


Figure 12b. --Critical depth, z_{cr} , vs. transition length, L , for slope and soil conditions assumed in figure 11.

CONCLUSIONS

Mathematical relationships have been derived to describe the failure surfaces in slopes where the assumptions of the infinite slope theory are valid. These relationships are general in that they can be applied to conditions of seepage wherein the piezometric level is at any depth below ground surface, provided that seepage is parallel to the slope. The relationships can also be adapted to layered systems, with or without seepage, provided that layering is parallel to the slope. This can most easily be accomplished by treating the material lying above a particular layer as simply a surcharge, or by converting the overlying layers to an equivalent depth of the material for which computations are being made. Use of a digital computer will facilitate computations.

Applicability of the infinite slope theory to real slopes has been discussed briefly, and it is concluded that no general "rule of thumb" or other criteria can be used to assess its applicability. Each slope must be judged according to its length and according to the soil characteristics and seepage conditions.

A simplified procedure to account for transition from the active to passive stress states within a long failure mass also has been presented and discussed. It is suggested that the simple transition-length idea applied herein to uninterrupted slopes might also be useful in the analysis of some cut slopes.

General solutions for the failure surfaces in slopes where the assumptions of the infinite slope theory are valid have been derived. The solutions are applicable to layered systems and to any seepage conditions provided that both layering and ground water flow are parallel to ground slope. It is concluded that the infinite slope theory is of limited applicability unless modified. A modification to enable transition from the active to passive stress states is suggested.

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APPENDIX

Symbols Used in This Report

A, a, a' = parameters in equations for failure surfaces;

B, b, b' = parameters in equations for failure surfaces;

c = cohesive strength;

k = parameter in equations for failure surfaces;

L = length of transition from active to passive stress states, measured parallel to ground slope;

l_{1A} = length of active failure surface measured parallel to ground slope for case when phreatic surface coincides with ground surface;

l_{1P} = length of passive failure surface measured parallel to ground slope for case when phreatic surface coincides with ground surface;

l_{2A} = length of active failure surface measured parallel to ground slope for case when phreatic surface lies between ground surface and critical depth;

l_{2P} = length of passive failure surface measured parallel to ground slope for case when phreatic surface lies between ground surface and critical depth;

l_{3A} = length of active failure surface measured parallel to ground slope for case when phreatic surface lies below critical depth;

l_{3P} = length of passive failure surface measured parallel to ground slope for case when phreatic surface lies below critical depth;

$m = \tan \alpha_f$;
 n = coordinate normal to ground surface;
 $\bar{n}$ = normal stress acting on rupture plane;
 p = resultant stress acting on plane parallel to ground slope;
 r = resultant stress acting on vertical plane;
 S = seepage force per unit area, and generalized incremental shear stress;
 s = coordinate parallel to ground surface;
 t = tangential stress acting on rupture plane;
 u, v = parameters in equations for failure surfaces;
 x = horizontal coordinate of point on failure surface measured from intersection of failure surface with ground surface;
 x_0 = horizontal coordinate of intersection of failure surface with phreatic surface in (x, y) coordinate system;
 x' = coordinate of point on failure surface measured parallel to ground slope from intersection of failure surface with ground surface;
 y = vertical coordinate of point on failure surface measured from intersection of failure surface with ground surface;
 y' = coordinate of point on failure surface measured vertically below ground surface;
 z = vertical depth below ground surface;
 z_1 = critical depth when phreatic surface coincides with ground surface;
 z_2 = critical depth when phreatic surface lies between ground surface and critical depth;
 z_3 = critical depth when phreatic surface lies below critical depth;
 z_{cr} = critical depth;
 z_w = vertical depth of phreatic surface below ground surface;
 α = slope of line from origin of planes to point on Mohr stress circle with respect to horizontal;
 α' = angle between tangent to rupture surface and ground surface;
 α_f = angle of line connecting origin of planes with point of tangency of Mohr stress circle with strength envelope;
 β = angle of obliquity beneath phreatic surface;
 γ_b = buoyant unit weight of soil below phreatic surface;

γ_{sat} = saturated unit weight of soil beneath phreatic surface;
 γ_t = unit weight of soil above phreatic surface;
 γ_w = unit weight of water;
 η = transformed coordinate ($= z - z_w$);
 η_0 = transformed coordinate at phreatic surface ($= 0$);
 θ = slope of ground surface;
 λ, λ_0 = parameters in Frontard's solution;
 $\bar{\sigma}$ = effective normal stress;
 $\bar{\sigma}_0$ = normal stress coordinate of center of Mohr stress circle;
 $\bar{\sigma}_a$ = effective normal stress on plane parallel to ground surface;
 $\bar{\sigma}_b$ = effective normal stress coordinate of origin of planes on Mohr stress circle;
 $\bar{\sigma}_c$ = effective normal stress on plane oriented at angle α and depth z ;
 $\bar{\sigma}_n$ = effective normal stress on plane parallel to ground surface;
 $\bar{\sigma}_s$ = effective normal stress on plane normal to ground surface;
 $\bar{\sigma}_x$ = effective normal stress coordinate of point of tangency of Mohr stress circle with strength envelope;
 τ = shear stress;
 τ_0 = shear stress coordinate of center of Mohr stress circle ($= 0$);
 τ_a = shear stress on plane parallel to ground surface;
 τ_b = shear stress coordinate of origin of planes on Mohr stress circle;
 τ_c = shear stress on plane oriented at angle α and depth z ;
 τ_{ns} = shear stress on plane parallel to ground surface;
 τ_{sn} = shear stress on plane normal to ground surface;
 τ_x = shear stress coordinate of point of tangency of Mohr stress circle with strength envelope; and
 ϕ = angle of internal friction.

GONSIOR, MICHAEL J., WILLIAM S. HARTSOCK, and GLEN L. MARTIN
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**A COMPARISON OF
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USDA Forest Service
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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Roger R. Bay, Director

THE AUTHORS

GENE D. AMMAN is Entomologist on the Population Dynamics of Primary Bark Beetles research work unit in Ogden, since joining the Intermountain Station in 1966. From 1958 to 1966 he was Entomologist with the Southeastern Forest Experiment Station in Asheville, N.C. Dr. Amman received both B.S. and M.S. degrees in Zoology from Colorado State University, and the Ph.D. in Forest Entomology from the University of Michigan. He is author of numerous publications concerned with ecology, dynamics, and control of mountain pine beetle and balsam woolly aphid populations.

LYNN A. RASMUSSEN is Biological Technician on the Population Dynamics of Primary Bark Beetles research work unit in Ogden. He earned the B.S. degree in Zoology from Utah State University. Mr. Rasmussen had experience on several bark beetle control projects before joining the Intermountain Station in 1965. He has authored several publications concerned with biology and behavior of the mountain pine beetle.

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ABSTRACT

Populations of the mountain pine beetle, Dendroctonus ponderosae Hopkins, were sampled by both radiographic and bark-removal methods in standing lodgepole pine, Pinus contorta Douglas. Estimates of live beetle numbers based on the two methods were comparable. However, the radiographic method is not recommended for field sampling because it is more costly and the causes of beetle mortality usually cannot be determined. In addition, beetle populations in areas radiographed were adversely affected, probably because of drying of wood and bark, which resulted in erroneous estimates of brood survival and distorted sex ratios.

INTRODUCTION

Radiography as a tool to sample populations of the mountain pine beetle, *Dendroctonus ponderosae* Hopkins, in lodgepole pine, *Pinus contorta* Douglas, was tested in the field. The objective was to determine whether radiography might prove to be a better method of sampling mountain pine beetle populations than the bark-removal method (Carlson and Cole 1965) currently used by this research work unit¹ to obtain life-table data.

Following a cohort of bark beetles through development would be more desirable than obtaining sample estimates from different cohorts. Radiography makes possible such study of cryptic forest insects, and has proved valuable in studying laboratory populations of bark beetles when frequent radiographs could be made (Berryman and Stark 1962a; Johnson and Molatore 1961). However, little field use has been made of radiography in population studies of forest insects.

Knight and Albertin (1966) used radiography in the field to study several insects, including borers, *Oberea schaumii* LeConte and *Saperda concolor* LeConte, in aspen, *Populus tremuloides* Michx., and the white pine weevil, *Pissodes strobi* (Peck), in jack pine, *Pinus banksiana* Lamb. Radiography currently is employed by C. J. DeMars (Entomologist, Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif., personal communication, July 27, 1973) to sample western pine beetle, *Dendroctonus brevicornis* LeConte, populations. The western pine beetle spends much of its developmental time in the outer bark of ponderosa pine, *P. ponderosa* Lawson. Infested bark is removed from trees, taken to the laboratory, and radiographed. Time is saved and accuracy is improved in counting forms on radiographs since the other method entails dissection of thick bark to find insects for direct counting (DeMars 1963). Similar findings were reported for the southern pine beetle, *D. frontalis* Hopkins, when bark samples from short leaf pine, *P. echinata* Miller, were radiographed (Fatzinger and Dixon 1965). However, removal of bark for radiographing still represents a destructive sampling technique and prevents workers from following a cohort through development.

Unlike larvae of the western and southern pine beetles, mountain pine beetle larvae in the thin bark of lodgepole pine feed and pupate primarily in the phloem layer against the sapwood surface. Consequently, removal of bark samples for radiographing would also expose larvae for direct counting. Therefore, any advantage of using the radiographic method in the field would be in the accuracy and speed of sampling beetles *in situ*. Radiographic sampling has been shown to give accurate counts of mountain pine beetles in bark and wood slabs of lodgepole pine in the laboratory (Amman and Rasmussen 1969).

¹ Population dynamics of primary bark beetles.

METHODS

Twelve beetle-infested lodgepole pines were selected for sampling over a period of time on the Wasatch National Forest south of Evanston, Wyoming. Four of the trees were 20 to 28 cm d.b.h., four trees 30 to 36 cm d.b.h., and four trees 38 cm and larger d.b.h. A chain saw was used to cut two vertical slots into the trunk of each tree for film placement, a technique explored by Berryman and Stark (1962b). This procedure resulted in a "slab" up to 5 cm thick approximately 75 cm above ground level; slots were located at random with respect to cardinal direction (fig. 1). Slots were used because radiographing the entire tree would (1) superimpose images of broods from the near side upon those on the far side, (2) require a much greater exposure time, and (3) result in radiographs of low contrast. The slots were about 20 by 25 cm to accommodate Kodak AA Ready Pack® film of that size, and were open only on one side in the larger trees to slow the rate of tissue drying. In the smaller trees, the trunk was not large enough to keep one side of the slot closed; consequently, slots were open on both sides. However, all slots were sealed with caulking cord to slow the rate of drying between sample dates.

Metal staples were placed in the corners of 15.2-cm² areas to be radiographed. Staples were visible on the radiographs and delineated areas from which population counts would be made. During development of the beetle, radiographs were obtained October 14, 1969, June 2, 1970, and June 30, 1970. Plastic screen cages, 15.2 cm², to which test tubes had been attached, were stapled over the area delineated by the staples after the last sample. Emerging insects were collected weekly from the test tubes, and numbers, sexes, and sizes were recorded.

Figure 1.--A chain saw was used to cut vertical slots in trees for film placement.



For purposes of comparison, two 15.2-cm² areas of bark within 31 cm of breast height were removed from the trees each time populations were radiographed. All insects, mountain pine beetle egg galleries, and gallery starts in the samples were counted. Plastic screen cages also were stapled on the trees in this area to collect insects emerging from the bark.

Moisture content of the trees was determined by means of an electrical resistance meter. Radiographic expose time was adjusted according to moisture content. Exposure curves for different slab thickness-moisture content combinations (fig. 2) were presented by Amman and Rasmussen (1969).

A portable Picker® X-ray machine with up to 110-kV output was used. All radiographs were taken at 25 kV, 5 mA, and at a 51-cm film distance. The 25 kV level gave better contrast than higher kilovoltage levels in laboratory tests (Amman and Rasmussen 1969). A cord that allowed the operator to be at least 12.5 m from the tube head during operation was used to protect him from possible radiation exposure. All legs of the quadruped stand telescoped for rapid height adjustment; wheels, mounted on the rear set, facilitated movement of the head from tree to tree. A 1,500-watt gasoline-powered alternator provided electricity for the unit. All equipment was easily moved by two men.

Because of trunk curvature, thickness of the area radiographed varied from about 5 cm in the center to about 2 cm on the outer edge. To avoid overexposure of sample portions thinner than 5 cm, an aluminum foil filter, that thickened laterally from the center, was placed over the sample area. The number of sheets of foil ranged from two near the center to six at the outer edge of the sample.

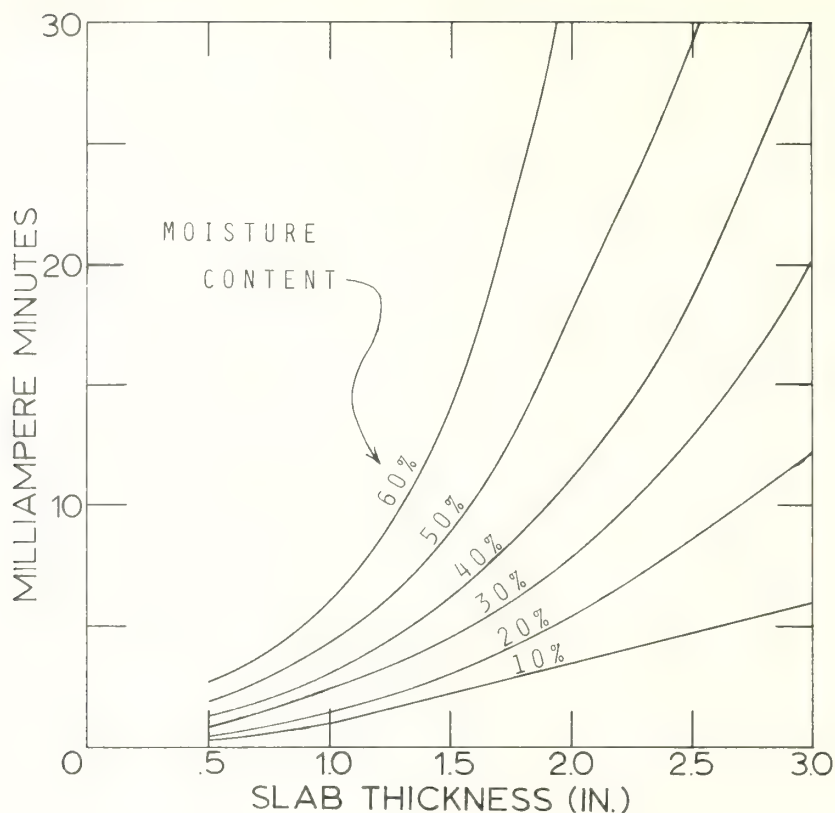


Figure 2.--X-ray exposure curves for wood and bark slabs (lodgepole pine) of different thickness and moisture content when the X-ray unit is operating at 25kV, 5mA, using a 51-cm (1 inch = 2.54 cm) target film distance (from Amman and Rasmussen, *J. Econ. Entomol.* 62:631-634, 1969).

Radiographs were processed and then interpreted independently by two observers. A light table, on which all light except for a 15.2-cm² area had been blocked out, was used for radiograph interpretation. Insects and their identification were recorded on mattex acetate placed over the radiograph. Counts of insects and stages were made from the overlays.

Data were analyzed by means of analysis of variance. The comparisons made between radiographic and bark-removal sampling were based on averages of estimates obtained by both observers.

RESULTS AND DISCUSSION

An evaluation of the radiographic method of sampling mountain pine beetle populations was based on both statistical and operational considerations.

Population estimates.--Assuming negligible location effects, no significant difference at the 0.05 level of probability was revealed among population estimates obtained by using the bark-removal method and estimates made from radiographs for any of the three sample dates (table 1). One source of difference was noted between estimates obtained by the two methods for the first sample; eggs could be counted in bark samples, but not on radiographs. As observed previously (Amman and Rasmussen 1969), radiographing mountain pine beetles through wood precluded detection of the slight difference in density of eggs. Eggs of the western pine beetle have been seen on radiographs when only bark was radiographed (C. J. DeMars, personal communication July 27, 1973). The authors detected no significant difference between methods for estimates of centimeters of egg gallery nor of the number of gallery starts. Therefore, estimates from radiographs appear to be comparable to those obtained by bark-removal sampling.

Comparisons of estimates made from radiographs by the two observers revealed no significant difference for brood populations and centimeters of egg gallery (table 1). However, the observers gave significantly different estimates for the number of gallery starts ($P < 0.01$). With the exception of gallery starts, observer differences are small and adequately trained observers can be expected to give comparable estimates from radiographs.

Table 1.--*Comparison of estimates from bark-removal and radiographic sampling.*

	Bark-removal sampling	Radiographic sampling ¹	Significance
-----Average/30.4 cm ² -----			
Brood number			
Observation 1	215.5	177.5	P > 0.10
Observation 2	83.2	78.3	P > 0.10
Observation 3	48.2	40.6	P > 0.10
Gallery cm	261.1	238.3	P > 0.10
Gallery starts	10.0	8.9	P > 0.10

¹ Estimates made by two observers were averaged and the average was compared with the estimates obtained by bark-removal sampling.

Table 2.--*Comparison of observer estimates made independently from the same sets of radiographs.*

	Observer 1	Observer 2	Significance
-----Average/30.4 cm ² -----			
Brood Number			
Observation 1	171.5	183.5	P > 0.05
Observation 2	82.9	73.6	P > 0.10
Observation 3	45.2	36.0	P > 0.10
Gallery cm	234.4	242.1	P > 0.10
Gallery starts	6.3	11.5	P < 0.01

Time.--An analysis of time required to accomplish sampling by the two methods demonstrated that the bark-removal method is much faster than the radiographic method. Time required for the first sample averaged 38.1 min per sample for the radiographic method compared to only 16.3 min per sample for the bark-removal method (table 3). Time required to accomplish the radiographic sample decreased during the second and third samplings because no new slots had to be cut in the trees. In addition, fewer insects in the last two samples speeded interpretation of radiographs. Also, a slight saving occurred in exposure time, which changed from an average of 1.4 min per sample for the first sample date to 0.78 min per sample for the last two sample dates because of decreasing moisture in the wood and bark. Ratios of time (bark removal method: radiographic method) ranged from 1:2.35 min per sample for the first sampling date to 1:1.66 min per sample for the third sampling date (table 3).

Table 3.--Time analysis of radiographic and bark-removal methods to sample mountain pine beetle populations.

	Observation		
	1	2	3
RADIOGRAPHIC METHOD			
Cutting slots in trees	11	11	11
Setting up and taking down equipment	60	60	60
Determining moisture content of trees	60	60	60
Radiographing and moving equipment from tree to tree	300	285	300
Sealing saw slots in trees	60	60	60
Developing and fixing film	60	60	60
Interpreting radiographs	257	127	80
Summarizing counts from overlays	60	48	44
Totals	917	700	649
Average/sample	38.2	29.2	27.0
BARK-REMOVAL METHOD			
Removing bark and counting insects	360		
Coating exposed wood with wax	30		
Total	390		
Average/sample	16.3		
Ratios (bark-removal:radiographic) 1:2.35 1:1.79 1:1.66			

One might expect the saving of time experienced with radiographic sampling when insect numbers were fewer to carry over to bark-removal sampling as well. However, this saving did not occur because more time was required to remove the drier and tighter bark in the latter samples.

Cost.--The initial cost of equipment needed to sample populations by the two methods was not considered; only the cost of expendable items used during the sampling process and sampling time were evaluated. The radiographic method cost a total of about \$46, or 64 cents per sample, more for materials than the bark-removal method. Costs were film \$32, developer \$7, and fixer \$7.

Total costs for time (based on GS-5 level) and materials follow: bark-removal method, \$1.01 per sample; radiographic method, first date, \$3 per sample, second date, \$2.44 per sample, and third date, \$2.31 per sample.

Assessment of mortality factors.--A major disadvantage of the radiographic method was the inability of the observers to assess mortality from the radiographs. predators could be seen and counted on the radiographs. The only one of consequence was *Medetera aldrichi* Wheeler (Diptera: Dolichopodidae). Dead beetles that had died completely were not often detected; those that were, usually could not be assigned to specific mortality causes. In addition, larvae that had recently died, but retained much moisture, could not be distinguished from living larvae. The bark-removal

sampling technique is definitely superior in this respect because the cause of death of most larvae can be determined. Consequently, the bark-removal sampling method will continue to be the choice for life-table sampling of mountain pine beetles where assessment of mortality factors is of primary concern.

Brood survival.--Although estimates of brood by the bark-removal and radiographic methods were comparable, the number of brood that completed development and emerged was only 4.0 adults per 30.4 cm² for the radiographed areas compared to 27.8 per 30.4 cm² for nonradiographed areas. In addition, the sex ratio was more in favor of females in radiographed areas than in nonradiographed areas--1:2.50 compared to 1:1.67 (males to females). A greater rate of drying in radiographed areas is suspected of causing these differences (unpublished data on file at Intermountain Forest and Range Experiment Station, Ogden, Utah).

Bluestain fungi introduced by the parent beetles interfere with movement of water in the infested tree (Nelson 1934). However, after the initial sample was taken, bark and wood in the area sampled by the bark-removal method appeared to contain more moisture than that sampled by the radiographic method. The vertical slots made by the saw to accommodate the film may have prevented moisture from moving horizontally from inner sapwood to outer sapwood and bark being radiographed. In addition, evaporation took place from the cut surfaces.

The amount of radiation received by the developing brood should not have caused the differences noted; no such abnormality was observed during laboratory investigations. In addition, the greatest total exposure to which any group of beetles was subjected for the three sample dates was about 800 R. This exposure was far below that generally found to sterilize insects or to interfere with insect behavior. For example, Davich and Lindquist (1962) found that at an exposure of 2,500 R, behavior and egg laying were about normal in the boll weevil (*Anthonomus grandis* Boheman).

Average size of mountain pine beetle brood adults did not appear to differ significantly between radiographed and nonradiographed areas: males in radiographed areas averaged 4.64 mm in length compared to 4.75 mm for males from nonradiographed areas; females in radiographed areas averaged 5.07 mm in length compared to 5.11 mm for nonradiographed areas (table 4).

Radiographic quality.--A problem that affected radiographic quality was unequal moisture content of the bark and wood within some of the radiographed areas. Where moisture was uniform, high quality radiographs were obtained (fig. 3); however, where moisture was uneven, radiographs were of unequal density and difficult to interpret (fig. 4). Streaks of high moisture content occurred where bluestain fungi were absent; absence was the result of beetle attacks that left some areas of bark lightly infested and, consequently, uninfected by bluestain fungi. Uneven radiographic exposure occurred when the probe for the electrical resistance meter was unknowingly placed in a moisture streak. This error resulted in overexposure of the radiograph for the areas surrounding the moisture streak. A less serious error occurred when the moisture probe was placed in fungus-infected wood near a moisture streak, which resulted in underexposure of the moisture streak. Usually, this area contained few larvae from nearby galleries; consequently, this error would not have affected the total count as much as that of the first type. Where a moisture streak is indicated on the first radiograph, possible solutions are either to take two radiographs of the area (one adjusted to the moisture streak, the other to the area surrounding the streak) or to develop a filter to reduce exposure of the area surrounding the streak. Poor radiographs necessitated a return trip to the field to retake radiographs at a more optimum exposure. A portable daylight developer unit would provide on-the-spot development; poor radiographs could be retaken immediately.

Table 4.--Number, size, and sex ratio of beetles emerging from the same trees where radiographic and bark-removal sampling were used.

	Number ¹	Average length	Standard deviation	Number 30.4 cm ²

RADIOGRAPHIC METHOD				
Male	6	4.64	0.62	1.0
Female	15	5.07	.58	2.5
Unidentified ²	<u>3</u>	--	--	.5
Totals	24			4.0
BARK-REMOVAL METHOD				
Male	54	4.75	.49	9.0
Female	90	5.11	.51	15.0
Unidentified ²	<u>23</u>	--	--	3.8
Totals	167			27.8

¹ Sex ratios (males to females) are 1:2.50 in radiographed areas, and 1:1.67 in nonradiographed areas.

² Beetles could not be sexed because of broken abdomens.

Figure 3.--Radiographs of good quality can be produced where moisture content of wood and bark is uniform and a filter is used to prevent overexposure of thin areas.





Figure 4.--Radiographs of poor quality result when moisture content of wood and bark is not uniform. Light streak represents area of high moisture content, the result of unequal distribution of bluestain fungi.

The radiographic method does not appear to offer any clear-cut advantage over the bark-removal method of sampling field populations of mountain pine beetles at this time. Although estimates of live beetle numbers obtained by the two methods were comparable, disadvantages of the radiographic method should be taken into account. These are (1) costs of both time and material; (2) difficulty in detecting dead beetles on radiographs and in assessing specific causes of mortality; and (3) lower emergence of brood adults, but higher female survival rates in radiographed areas.

Although these disadvantages of the radiographic method exist when sampling field populations of mountain pine beetles, radiography could be a useful technique for studying some aspects of bark beetle biology and behavior. In addition, radiography will continue to be an important means for studying laboratory populations of bark beetles.

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AMMAN, GENE D., and LYNN A. RASMUSSEN

1974. A comparison of radiographic and bark-removal methods for sampling of mountain pine beetle populations, USDA Forest Serv. Res. Pap. INT-151, 11 p., illus. (Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.)

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10. INT-152

EVENT PROBABILITIES ESTIMATED BY REGRESSION

David A. Hamilton, Jr.

YES

NO

BAD

CONDITION

GOOD



USDA Forest Service Research Paper INT-152, 1974
INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHOR

DAVID A. HAMILTON, JR., is a Research Forester working in timber measurements and management planning research at the Forestry Sciences Laboratory, Moscow, Idaho. Since receiving his Ph.D. in forestry from Iowa State University in 1970, he has been working on the sampling and modeling of forest mortality.

EVENT PROBABILITIES ESTIMATED BY REGRESSION

David A. Hamilton, Jr.

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION

Forest Service

U.S. Department of Agriculture

Ogden, Utah 84401

Roger R. Bock, Director

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ABSTRACT

Describes an algorithm for fitting the relationship between a dichotomous dependent variable and a number of independent variables. The specific functional form utilized is the logistic function. The algorithm, proposed and programed by Walker and Duncan (1967), has been generalized by adding a subroutine to handle data transformations and by introducing procedures to handle data sampled with unequal probability. A user's guide discusses makeup of program control cards, data transformation capabilities, program output, and program-generated errors.

INTRODUCTION

The procedure discussed in this paper evolved from efforts to develop a model for estimating the probability of mortality for an individual tree, as a function of individual tree and crown characteristics. However, the algorithm discussed may be applied to describe the relationship between dependent and independent variables when the dependent variable is dichotomous.

In mathematics, a dichotomous variable is one that may assume only one of two distinct values. For estimating the probability of individual tree mortality, the dichotomous dependent variable assumes the value 1 when a tree dies during the measurement interval and otherwise assumes the value 0. The independent variables are diameter at breast high (d.b.h.), crown ratio, crown width, tip character, and insect or disease damage.

A dichotomous dependent variable may pose difficulties in the analysis of data.^{1/} The model frequently applied in this situation is a linear regression model of the form

$$E(y|x_1, \dots, x_n) = \beta_0 + \beta_1 x_1 + \dots + \beta_n x_n$$

where

x_i = i th independent variable ($i = 1, \dots, n$)

β_j = j th regression coefficient ($j = 0, 1, \dots, n$)

$$E(y|x_1, \dots, x_n) = P(y=1|x_1, \dots, x_n)$$

A major difficulty in using a linear regression model is that probabilities greater than 1 or less than 0 may occur. This is most likely to occur when an independent variable assumes a value near or outside the limits of the initial data set

^{1/}This analysis is different from discriminant analysis, which is used to assign individual observations to one of a finite number of classes. The analysis discussed in this paper, however, is designed to estimate the probability that any given observation will assume one of two distinct classes.

Neter and Maynes (1970) have cited several reasons for expecting a curvilinear rather than a linear relationship when the dependent variable is dichotomous. Thus, a nonlinear model appears to be preferable.

Neter and Maynes have also questioned the meaning or usefulness of the correlation coefficient when the dependent variable is dichotomous. When the true relationship is nonlinear, the correlation coefficient does not apply. Even when the true relationship is linear, the meaning of the correlation coefficient is not clear. Neter and Maynes (1970) have demonstrated that when the dependent variable is dichotomous the correlation coefficient can attain a value of 1 only when the independent variable is also dichotomous. Thus, we are usually unable to judge an estimated correlation coefficient against the maximum value 1 that indicates a perfect relationship.

Walker and Duncan (1967), and others have suggested the logistic function in place of the linear model. This model has the form

$$E(p|x_1, \dots, x_n) = \{1 + \exp[-(\alpha_0 + \beta_1 x_1 + \dots + \beta_n x_n)]\}^{-1} \quad (1)$$

and restricts probability estimates to the closed interval $[0,1]$.

Another difficulty in analyzing a dichotomous dependent variable is that we must assume that the variance is nonhomogeneous. Thus, weighted regression must be used to estimate the regression coefficients.

Walker and Duncan (1967) have suggested an algorithm and computer program for fitting the logistic model. Modifications of the computer program and of the algorithm to handle data sampled with unequal probability and four sample analyses are discussed in this paper.

The discussion of the algorithm will utilize matrix notation. Equation (1) is rewritten in matrix notation as

$$p = [1 + \exp(-x' \beta)]^{-1} + \epsilon \quad (2)$$

where

p = probability of the occurrence of an event

$\hat{p}$ = estimate of p

x = vector of independent variables

β = vector of regression coefficients

$E(\epsilon) = 0$

$\text{Var}(\epsilon) = p(1-p)$

APPLICATIONS OF MODIFIED PROGRAM

Mortality

The program has been used in two independent situations to estimate the mortality of individual tree mortality. Permanent sample plots established in western white pine (*Pinus monticola* Dougl.) on the Deception Creek Experimental Forest and in the Kaniksu National Forest were measured at 5-year intervals for 20 years. A preliminary analysis of these data produced the following model for predicting mortality of individual trees:

$$M = 1 + \exp[-0.2735 + 0.2746(\bar{C}) + 2.5054(\bar{C})^2]$$

where

$\bar{C}$ = crown ratio

$\bar{C}$ = position in the tree basal area distribution

Lee (1971) tabulated mortality rates for lodgepole pine by 2-inch-diameter class. A functional expression describing this relationship must be developed if it is to be used in a computer program. Such an expression demonstrates another use for this analysis and illustrates the versatility of the logistic function.

The logistic function is expressed graphically as a U-shaped curve. Because Lee's data indicate that a U-shaped curve describes the relationship between mean stand d.b.h. and mortality, the independent variable must be transformed to fit the relationship. The sets of transformed variables $\bar{C}$ and $\bar{C}^2$, and $1/\bar{C}$ and $1/\bar{C}^2$ are available for the potential of fitting either this U-shaped distribution or a bell-shaped distribution. For Lee's data the model is

$$M = 1 + \exp[5.002 + 0.30775(\bar{DBH}) + 0.0174(\bar{DBH})^2]$$

where

$\bar{DBH}$ = mean stand d.b.h.

Cull Estimation

The logistic function was used twice to estimate cull volume on the Kaniksu National Forest. First it was used to predict the probability that a tree of given characteristics was a cull tree. The dependent variable assumed the value 1 when the tree was a cull tree and otherwise assumed the value 0. The independent variables were DBH and a measure of stand density, $\frac{V/a}{DBH}$. (V/a is gross cubic foot volume per acre.) For hemlock the resulting model is

$$\hat{P} = \{1 + \exp[9.1010 - 0.3696(DBH) - 0.00348(\frac{V/a}{DBH})]\}^{-1}$$

The second use of the function was to estimate the probability that a noncull tree had some cull volume. The dependent variable assumes the value 1 if a tree classified as noncull has some cull volume and otherwise assumes the value 0. The independent variables were DBH and $(\frac{V/a}{DBH})$. For the cedar-hemlock species mix, the model for predicting the probability of cubic-foot defect in noncull trees is

$$\hat{P} = \{1 + \exp[4.494 - 0.3776(DBH)]\}^{-1}$$

Cubic-foot defect in noncull trees was estimated by the product of $\hat{P}$ and a linear function that estimates cubic-foot defect in trees having cull as a function of DBH and $(\frac{V/a}{DBH})$.

Canker Inactivation

The algorithm was also used to investigate levels and trends of natural inactivation of western white pine blister rust cankers and thereby to determine causal relationships for natural inactivation and to explain the variation that occurs in natural inactivation.

The following model demonstrates the relationship between the probability of a canker becoming inactive in the coming year ($\hat{P}$), stand elevation (EL), canker age (CA), and branch diameter (BD):

$$\hat{P} = \{1 + \exp[0.883 + 0.0323(EL) - 0.304(CA) + 1.617(BD)]\}^{-1}$$

Readers unconcerned with the theoretical development of the algorithm and its modifications may omit reading the next four sections. Enough detail has been provided in the section "Guides for the Use of Risk", page 12, to run the program.

SAMPLING ASSUMPTIONS OF ALGORITHM

When data have been collected according to a sampling design, each observation represents a number of similar observations. When this number (weight or blowup factor) varies from observation to observation (i.e., when sampling is other than equal probability sampling), the effect on the relationship of interest must be recognized, particularly in estimating individual tree mortality.

Because of the distribution of mortality in endemic situations, wide areas must be sampled to assure an adequate representation of dead trees. It would not be feasible to measure each green tree in the area; therefore, only a subsample of the green trees is measured. In this situation not all trees are sampled with equal probability. For example, assume 5-acre plots have been selected for obtaining mortality counts. A 1/5-acre plot is established within each 5-acre mortality plot to obtain counts of green trees. Thus, dead trees have a relative weight of 1 and green trees have a relative weight of $5/(1/5) = 25$.

WALKER-DUNCAN ALGORITHM

RISK, the computer version of this algorithm, uses weighted least squares parameter estimation. Weights are estimated as the inverse of the standard deviation. A first-degree Taylor series expansion around a guessed value of β provides the linear function of the parameters required to make least squares a manageable estimation procedure.

An alternative form of the logistic function is given by

$$\ln [P/(1-P)] = x'\beta$$

Although this form of the logistic function can be fit by any linear regression program, it has disadvantages. The independent variables must either be discrete or must be partitioned into discrete classes. The set of all possible combinations of these classes defines a set of categories to which each observation is assigned. P is the proportion of the observations in each category for which the dependent variable is 1. Another disadvantage is that each category must contain enough observations to insure a meaningful value of P for that category. Thus, the form of independent variables is not only restricted by the alternative model, but also the data requirements are frequently greater than if equation (2) were used.

A unique feature of RISK is that parameter estimates are updated when each observation is added rather than only when each iteration is completed. Updating utilizes the following relationship reported by Bartlett (1951):

$$(X'X + xx')^{-1} = (X'X)^{-1} - \frac{(X'X)^{-1}xx'(X'X)^{-1}}{1 + x'(X'X)^{-1}x}$$

$(X'X)$ is the sum of squares matrix for those observations already in the solution, and xx' is the matrix of components added to each element of $(X'X)$ by the addition of the next observation. This relationship is verified by demonstrating that multiplication of the right-hand side of (3) by $(X'X + xx')$ yields the identity matrix.

This algorithm improves on alternative nonlinear regression algorithms in that starting values for the parameters are not required. Instead β_1 through β_n of equation (1) are set equal to 0. β_0 is calculated in RISK by solving the equation

$$\bar{y} = \beta_0 + \bar{x}\beta_1$$

for β_0 . $\bar{y}$ is the mean value of the dependent variable in the population (i.e., proportion of the observations for which the dependent variable is 1). If it is desirable to start the iteration at some other value of β_0 , a preferred value of β_0 may be specified.

Following each pass through the data, the resulting $(X'X)^{-1}$ matrix is corrected to remove the effects of the $(X'X)$ matrix used to start that pass. The parameter estimates are similarly corrected. These corrections are made by using the following formulas:

$$(X'X)_c^{-1} = [(X'X)^* - (X'X)_0]^{-1}$$

$$b_c = (X'X)_c^{-1} [(X'X)^* b^* - (X'X)_0 b_0]$$

where

$(X'X)_c^{-1}$ = corrected matrix

$(X'X)^*$ = inverse of the uncorrected $(X'X)^{-1}$ matrix

$(X'X)_0$ = prior $(X'X)$ matrix

b_c = corrected vector of parameter estimates

b^* = uncorrected vector of parameter estimates

b_0 = vector of starting values for parameter estimates

Matrix correction, which reduces the number of passes required for convergence, can be requested once within each pass through the data. Experience indicates, however, that savings in computations resulting from fewer passes are frequently offset by increased computations arising from matrix inversion.

MODIFICATION OF ALGORITHM

The original algorithm was modified to deal with unequal weighting of observations. An extension of the work of Bartlett (1951) demonstrates the inverse of the expression $(X'X + mXX')$ may be written as

$$(X'X + mXX')^{-1} = (X'X)^{-1} - \frac{(X'X)^{-1} mXX' (X'X)^{-1}}{1 + mX' (X'X)^{-1} X} \quad (4)$$

where m is the weight or blowup factor associated with each observation, x . This relationship may be verified by showing that the product of $(X'X + mXX')$ and the right-hand side of (4) yields the identity matrix.

The first degree Taylor Series expansion of the logistic function around a guessed value of the parameter vector, $\bar{\beta}$, may be expressed as

$$y_n^* = x_n' \beta / w_n + \epsilon_n$$

where for the n th observation in the population

$$y_n^* = p_n - (1 + \exp(x_n' \bar{\beta}))^{-1} + x_n' \bar{\beta} / w_n \quad (5)$$

p_n = observed value of dependent variable (either 0 or 1)

$$w_n = 1/\hat{P}_n \hat{Q}_n$$

$$E(\epsilon_n) = 0$$

$$\text{Var}(\epsilon_n) = \sigma^2 \hat{P}_n \hat{Q}_n$$

Let $Y = WY^*$ so that the weighted Normal Equations may be written as

$$X'W^{-1} X\beta = X'W^{-1} Y$$

which implies that the least squares estimator of β is

$$b = (X'W^{-1}X)^{-1}X'W^{-1}Y$$

Since W^{-1} is diagonal we can define W^* such that

$$W^*W^* = W \text{ (i.e., } w_n = 1/\hat{P}_n \hat{Q}_n \text{ and } w_n^* = \sqrt{w_n})$$

Then let $X^* = W^*X$ and

$$b = (X^{*'}X^*)^{-1}X^{*'}W^{-1}Y \quad (6)$$

A recursive relationship for estimating b_n results when equations (4), (5), and (6) are combined in the following manner:

$$\begin{aligned}
 b_{n_i} &= [(X^*{}^T X^*)_{n-1}^{-1} + m X_n^* X_n^{*T}]^{-1} [(X^*{}^T W^{-1} Y)_{n-1} + m X_n^* Y_n] \\
 &= \left\{ (X^*{}^T X^*)_{n-1}^{-1} - \frac{(X^*{}^T X^*)_{n-1}^{-1} m X_n^* X_n^{*T} (X^*{}^T X^*)_{n-1}^{-1}}{1 + m X_n^{*T} (X^*{}^T X^*)_{n-1}^{-1} X_n^*} \right\} [(X^*{}^T W^{-1} Y)_{n-1} + m X_n^* Y_n] \\
 &= b_{n-1} + \frac{(X^*{}^T W^{-1} X)_{n-1}^{-1} m X_n^* (Y_n - b_{n-1}^T X_n)}{1 + m X_n^{*T} (X^*{}^T W^{-1} X)_{n-1}^{-1} X_n^*}
 \end{aligned}$$

Iteration continues until the change in regression coefficients following two successive passes through the data satisfies the convergence criteria

$$\delta_i / [\tau + |b_i|]$$

where

δ_i = change in i th regression coefficient following successive passes through the data.

b_i = i th regression coefficient

η = convergence criteria

τ = small number to handle case where b_i approaches 0.

Applying equation (7) is similar to adding m identical observations to the solution between successive estimations of the set of parameters. Adding an observation with a large relative weight frequently drives the solution so far that the computer cannot distinguish the resulting estimate of P_n from either 0 or 1, which will terminate the iteration abnormally.

The computational difficulty just discussed has been minimized by setting a limit for the sum of successive weights. The effect of adding each weighted observation to the solution is accumulated. However, the parameter estimates used in the iterative estimation procedure are updated only when the sum of successive weights exceeds the set limit. The same procedures may be used to handle similar problems that arise when data sorting results in runs of 0's or 1's.

STATISTICAL CRITERIA FOR GOODNESS-OF-FIT

When the dependent variable is dichotomous, mean square error (the customary measure of goodness-of-fit for regression relationships) is not appropriate. The definition of mean square error demonstrates its inappropriateness as a measure of goodness-of-fit.

$$MSE = \sum_{i=1}^N \frac{(y_i - \hat{y}_i)^2}{N-r}$$

where N is the population size and r is the number of parameters to be estimated in the regression. y_i is always either 0 or 1 while $\hat{y}_i$ is a continuous variable in the range $(0 \leq \hat{y}_i \leq 1)$. The following proof shows that as N increases, the limiting value for the mean square error is 1 rather than 0, as is expected in most regression relationships.

When Y is a (0,1) variable, $\bar{Y} = \sum_{i=1}^N y_i / N = P$ and $\sum_{i=1}^N (y_i - \bar{Y})^2 = NPQ$ (Cochran 1963).

$$MSE = \sum_{j=1}^L \sum_{i=1}^{N_j} \frac{(Y_{ij} - \bar{Y}_{.j})^2}{P_{.j} Q_{.j}}$$

where L represents the number of arbitrary classes defined such that in each class $P_{.j}$ is approximately constant (i.e., $\approx P_{.j}$).

Thus

$$MSE \doteq \sum_{j=1}^L \sum_{i=1}^{N_j} \frac{(Y_{ij} - \bar{Y}_{.j})^2}{P_{.j} Q_{.j}}$$

$$\text{Within each class } \hat{Y}_{.j} \doteq \sum_{i=1}^{N_j} Y_{ij} / N_{.j} = \bar{Y}_{.j} = P_{.j}$$

so

$$MSE \doteq \sum_{j=1}^L \frac{1}{P_{.j} Q_{.j}} \sum_{i=1}^{N_j} (Y_{ij} - \bar{Y}_{.j})^2 = \sum_{j=1}^L \frac{1}{P_{.j} Q_{.j}} \sum_{i=1}^{N_j} (Y_{ij} - P_{.j})^2$$

This approximation improves as the number of classes increases and as the width of each class decreases.

Thus, $MSE \doteq \frac{r}{n-r}$ where r = number of parameters to be estimated and

$$\lim_{n \rightarrow \infty} MSE \doteq \lim_{n \rightarrow \infty} \frac{r}{n-r} = 0$$

RISK output includes three types of statistics that might be used to measure goodness-of-fit. These are a set of t tests that test whether each of the estimated parameters is significantly different from 0, an analysis of variance F test that tests the significance of the amount of variation explained by regression, and a chi-square table that evaluates goodness-of-fit over the range of predictions (e.g., $0 \leq \mu_j \leq 1$).

Each of these statistics tells us something different about the goodness-of-fit of a model. Walker and Duncan (1967) imply that the F statistic is the appropriate measure of goodness-of-fit for screening alternative models. Although I feel that the chi-square statistic is preferable for screening alternative models, the method used to measure goodness-of-fit is left to the discretion of the user.

RISK is not an efficient procedure for screening alternative sets of independent variables, especially when the data set is large. RISK seems to be most efficient for estimating parameters after the optimal set of predictor variables has been selected. The method proposed by Sterling and others (1969) based on information theory has been successfully used to select an optimal set of independent variables.^{2/}

^{2/}A computer program of the screening algorithm is documented by David A. Hamilton, Jr., and Donna Wendt, to be published as USDA Forest Service General Technical Bulletin.

GUIDES FOR USE OF RISK

RISK is a computer program written by Walker and Duncan (1967) that calculates the nonlinear regression coefficients of the logistic function utilizing the algorithm just discussed. The program has been modified to handle data with unequal sampling weights attached to each observation. The program is written in FORTRAN IV and has been run on an IBM 360/67. Requests for the program should be directed to:

Intermountain Forest and Range Experiment Station
Forestry Sciences Laboratory
Attention: David A. Hamilton, Jr.
1221 S. Main
Moscow, Idaho 83843

Control Cards

<i>Field Function</i>	<i>Value</i>	<i>Column</i>	<i>Unit</i>	<i>Format</i>
<u>Card 1</u>				
Problem identification		1-80	IDENT	20A4
<u>Card 2</u>				
Regressor set number	xx...x	1-10	ANRS	F10.0
Run number	xx...x	11-20	AN	F10.0
Number of parameters to be estimated (≤ 30)	xx...x	21-30	ANR	F10.0
Number of observations in population	xx...x	31-40	ANØ	F10.0
Is input file on cards?	Yes = 0	41-50	ATAPE	F10.0
No = input unit number containing input file				

Control Cards

Is default value for ϵ , (.0002), in the convergence criteria to be overridden? ^{3/}	Yes = desired value for ϵ	1-10	10	11-10
	No = blank			

Is default value for τ , (.01), in the convergence criteria to be overridden?	Yes = desired value for τ	61-70	TAB	11-10
	No = blank			

Card 5

Are the starting values for parameter estimates to be provided? ^{4/}	No = 0	1-10	10	11-10
	Yes = desired value of			

Code designating a missing value in an observation ^{5/}	xx...x	11-20	0	11-10
--	--------	-------	---	-------

Are the variables to be labeled on the computer output?	No = 0	1-10	XXLEM	11-10
	Yes = number of labels provided			

Limit for sum of weights ^{6/}	xx...x	51-10	ELIM	F10.0
--	--------	-------	------	-------

Card 4

Number of variables to be read for each observation (32)	XXXXX	1-5	11-10	5
---	-------	-----	-------	---

Card 5

NOTE: On card 5, the absolute value of A is the observation number at which matrix correction would occur.

^{3/}The default values for the parameters of the convergence criteria are satisfactory for most uses of RISK. If increased precision is desired, however, the value of ϵ should be decreased. Conversely, if less precision is required, ϵ can be increased.

^{4/}Starting values for the parameter estimates are generated by RISK. These are:

$$\beta_0 = 0 \quad (\beta_1, \dots, \beta_k)$$

$$\beta_0 = \text{solution of the equation } \tau = [1 + \exp(-\beta_0)]$$

$$\bar{y} = \text{mean value of dependent variable in the observation.}$$

An alternative value for β_0 may be specified on control card 5.

^{5/}Each missing value in the data should be coded. RISK deletes any observation that has one of the independent variables set equal to the missing value code.

^{6/}The limit for the sum of weights should normally be set equal to 0.5. However, if the data are sorted or if the observations have unequal weights, the resulting estimates of P may be driven to 0 or 1. When this occurs, the limit for the sum of weights should be increased until the difficulty is overcome.

<i>Field Function</i>	<i>Value</i>	<i>Column</i>	<i>Name</i>	<i>Format</i>
For J=1,...,16, should matrix correction occur within Jth pass through data? If so, is intermediate output desired? ^{2/}	No = 0	1-5	NIT(J)	I5
	Correction with intermediate output = -A	6-10 . . .		
	Correction without intermediate output = A			

NOTE: For passes J = 2,...,16, if no additional passes through the data are desired, NIT(J) is set equal to 9999.

Card 6

Format for reading card or tape input	1-80	F1000	20A4
---------------------------------------	------	-------	------

Card 7

Leader label for input file	1-80	ABEL	20A4
-----------------------------	------	------	------

NOTE: Omit card 7 if card input file is used.

Card 8

For J=1,...,VARLAB what is the Jth variable name or label?	xxxx	2-5 7-10 . . .	SX(J)	(1X,A4)
--	------	----------------------------	-------	---------

NOTE: Omit this card if VARLAB = 0

Card 9

Which field on card 8 contains the label for the dependent variable?	xxxxxx	1-5	NVAR(NR1)	I5
For K=2,...,NR what field on card 8 contains the label for the Kth independent variable?	xxxxxx	6-10 11-15 . . .	NVAR(K)	I5

NOTE: Omit this card if VARLAB = 0.

NOTE: Card input file inserted here if ATAPE = 0.

^{2/}Matrix correction removes the effects of the $(X'X)$ matrix used to start that pass through the data from both the resulting $(X'X)^{-1}$ matrix and the vector of regression coefficients. Requesting matrix correction within a pass through the data reduces the number of passes through the data required for convergence. However, experience has indicated that frequently any savings in computations resulting from fewer passes through the data are offset by increased computations arising from the additional matrix inversions.

Card 10,...,k

What is the Jth observation number for which intermediate output is desired?

1
6-10

NOTE: There must be at least one such card for each pass through the data.
NOTE: An NITF(J) value set equal to the total number of observations will terminate intermediate output for that pass through the data.
NOTE: Omit these cards if all NITF(J) = 0.

Data Preparation

A data transformation subroutine, titled TRNS, has been developed to assist the user with maximum flexibility in input data format. This routine has been written for each use of RISK. Input to TRNS is the observation vector read into the variable format specified by control card 6. The independent variable X(1) is set equal to 1 by the main program. The dependent variable, all additional independent variables, and the weight for the observation must be defined within TRNS. For the simplest case where no transformations are to be made, the following setup for TRNS would be adequate.

```
SUBROUTINE TRNS(D, NR, NR1, X, R)
  DIMENSION D(72), X(32)
  DO 1 I = 1, NR
    1 X(I) = D(I)
    X(NR1) = D(I)
    R = D(NR + 1)
  RETURN
END
```

The notation in this subroutine is defined as follows:

D = observation vector as it is read from input data.

NR = number of parameters to be estimated.

NR1 = subscript of dependent variable in the β vector (as defined in the main program).

X = vector of independent and dependent variables to be transformed.

R = weight or blowup factor for each observation.

This sample subroutine assumes that the first variable in the observation vector is the dependent variable (0 or 1), the variables 2 through NR are independent variables, and variable (NR + 1) is the weight or blowup factor that describes the number of similar observations represented by the sample observation.

Program Output

RISK provides a summary of the input and a description of the regression results. The summary of input begins with a tabulation of control information the user has provided to run the program. Also included are tables of means and standard deviations of all variables in the population. The final portion of this summary of input consists of three matrices: a matrix of correlation coefficients, an associated matrix of t statistics indicating the significance of the correlation coefficients, and a product moment matrix.

The output dealing with regression results may be broken into two sections: (a) A list of the parameter estimates and error mean square resulting from each of the passes through the data followed by the final parameter estimates and (b) the measures of goodness-of-fit. These measures are a table of t statistics, an analysis of variance table, and a table of chi-square statistics.

The first table of t statistics were calculated on the assumption that error mean square is 1 (i.e., the model provides a perfect fit of the data). The second table is calculated using the actual error mean square provided by the analysis of variance. Neither of these statistics is truly distributed according to the t distribution, because the $(X'X)^{-1}$ matrix is constructed utilizing estimated values of PQ as weights. The statistics in the first table are approximately normally distributed and the statistics in the second table are approximately distributed according to the t distribution. As the error in predicting P becomes negligible, these approximations improve.

The user may request intermediate output for any pass through the data that includes a matrix correction. This output consists of the $(X'X)^{-1}$ matrix and the vector of regression coefficients that exist at those points in the pass for which intermediate output is requested. This same output is provided following the final observation in any pass that included a matrix correction. The $(X'X)$ matrix is also printed at this time. The $(X'X)^{-1}$ and $(X'X)$ matrices both before and after correction, the regression coefficients before and after correction, and the regression coefficients that were used to start the pass are printed at the point of matrix correction.

Error Diagnostics

Six messages are generated by RISK to explain abnormal terminations of the program:

MORE THAN NC DATA CARDS HAVE BEEN INCLUDED IN THIS RUN

This diagnostic message is generated when there are more cards in the card input file than are specified, which could occur either from incorrectly counting the number of observations in the input data set or as the result of incorrectly preparing the set of control cards.

THE NUMBER OF REGRESSORS NR IS IN EXCESS OF THE PRESENT PROGRAM MAXIMUM OF 30

This diagnostic message is generated if the specified number of regressors, NR, is greater than 30. This check is made before the population of observations is read into the machine; if NR is greater than 30, program execution is terminated.

INCONSISTENCY BETWEEN ACTUAL AND SPECIFIC TAPE LABELS

When the population of observations are on tape or in a cataloged data set, if the leader label on input unit ATAPE is not identical to the label on control , the above diagnostic message is generated and program execution is terminated. This provides some assurance that you are reading the appropriate input file.

MATRIX INVERSION FAILURE, NGO = ---, I = ----, SINGULARITY AT J = --, WITH A(J,J)

This diagnostic message is generated when subroutine INVERT is unable to fully invert a matrix. The variable NGO in this message indicates at what point in the program the inversion failed. When NGO equals 1, the inversion failure has occurred at statement RISK2610. When NGO equals 999, the inversion failure has occurred at statement RISK5360. In all other cases, NGO will be a two or three digit number. The final digit indicates where in the program inversion has failed; the initial one or two digits indicate the iteration on which inversion failed. The various values of NGO are

where X is the iteration number on which matrix inversion fails. The variable I in this message is the number of the last observation added to the solution before inversion failed. J is the location in the matrix to be inverted that caused inversion failure, and A(J,J) is the actual value of the matrix element that caused inversion failure.

COEFFICIENTS HAVE DIVERGED TO POINT THAT POLYNOMIALS . . .

Occasionally for a sorted or weighted set of observations, the regression coefficients may be driven to the point where the estimates of $\hat{\beta}$ approach 0 or 1. This situation results in a division by 0, which would terminate program execution on the IBM 360/67; therefore, the value of P is checked and the above diagnostic message generated any time P is equal to 0 or 1.

When this message occurs, the user has two courses of action that may allow completion of the analysis: (a) Rearranging the data to eliminate the effects of sorting (unfortunately, this is frequently not feasible), and (b) increasing the input parameter ELIM (the limit for the sum of weights), which reduces the effect of both of large variability in the weights and of sorted data.

EXECUTION TERMINATED, SBX = ----

This diagnostic message is generated by circumstances similar to the one which generated the previous message. However, in this case, the regression coefficients have been driven to the point that P cannot be evaluated by the computer. If this occurs, the user has the two alternatives discussed for the previous diagnostic message.

DISCUSSION AND CONCLUSIONS

The logistic function is preferable to a linear model for describing the relationship between a dichotomous dependent variable and a set of independent variables. The algorithm discussed in this paper provides a valid method of estimating the parameters of the logistic function.

Both the algorithm and the computer program have been modified to handle data collected with arbitrary probability. This modification is of particular value in cases such as estimating tree mortality when it would not be feasible to measure all observations with equal probability.

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HAMMELTON, DAVID A., JR.

1971. Event probabilities estimated by regression. USDA Forest Service Res. Rep. IN-1452, 1 p., illus., determinantal, Forest and Range Experiment Station, Ogden Utah Station.

Describes an algorithm for fitting the relationship between a dichotomous dependent variable and a number of independent variables. The specific functional form utilized is the logistic function. The algorithm, proposed and programmed by Waller and Duncan (1967), has been generalized by adding a subroutine to handle data transformations and by introducing procedures to handle data sampled with unequal probability. A user's guide discusses makeup of program, control cards, data transformation capabilities, program output, and program-generated errors.

KEYWORDS: nonlinear regression, dichotomous dependent variable, computer coding, computer algorithm, logistic function, probability estimation.

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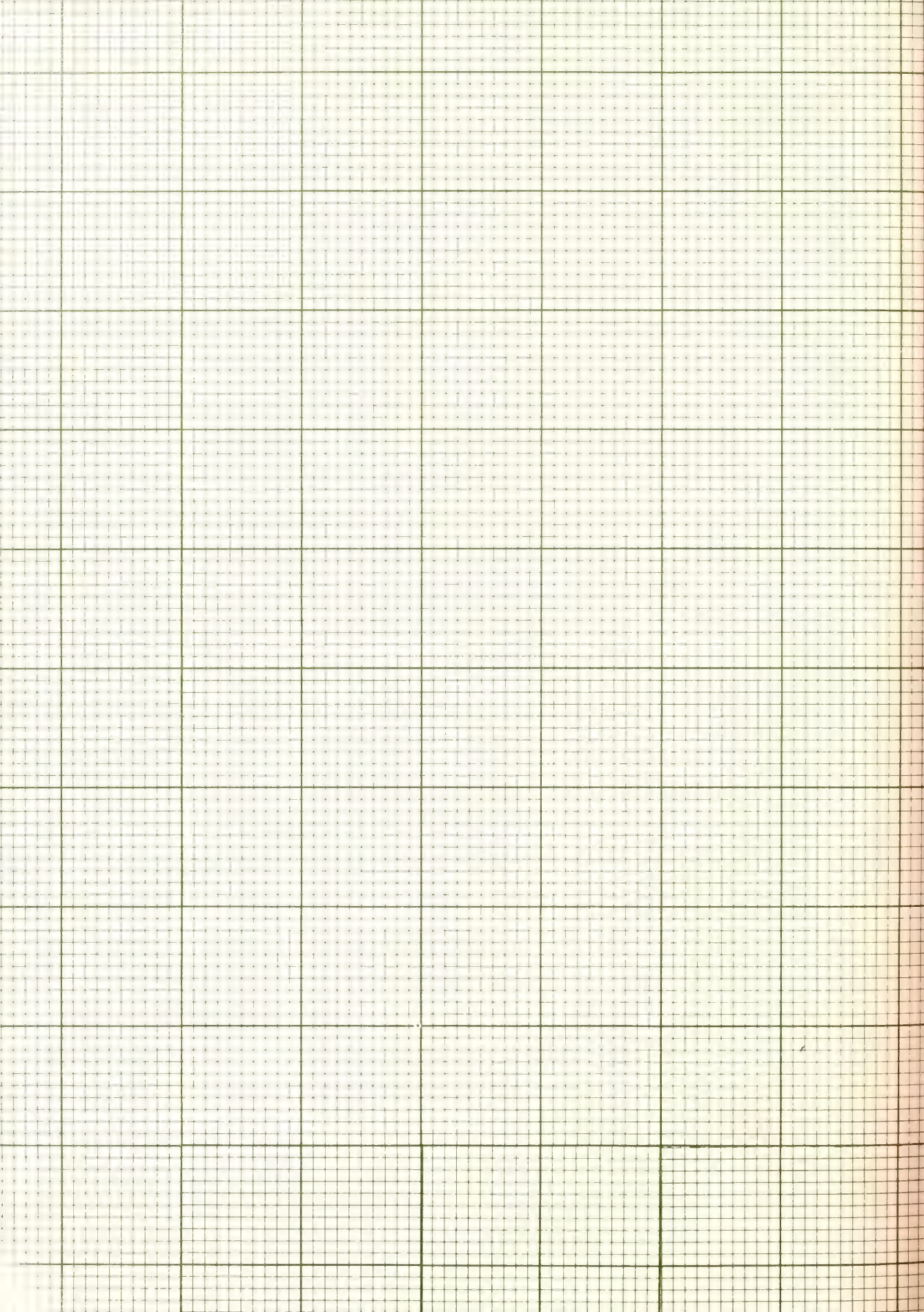
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FOREST FIRE RETARDANT: TRANSMISSION THROUGH A TREE CROWN

Hal E. Anderson



INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Ogden, Utah 84401

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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Roger R. Bay, Director

ABSTRACT

Increasing expenditures for forest fire retardant and the development of more efficient delivery systems have emphasized the need for more knowledge on the transmission and retention characteristics of wildland fuels. In a series of tests, retardant was cascaded from an airplane onto arrays simulating wildland fuels. The proportion of retardant retained increased as the fuel diameter and surface roughness of individual fuel elements increased. Equations describing retention were developed and were extended to actual field situations through published research on rainfall. Retardant transmission through a tree crown was modeled; results agreed with published findings on the transmission of rain.

INTRODUCTION

The use of chemical fire retardants has increased greatly in recent years. In 1970, over 17 million gallons of fire retardants were applied from aircraft (George 1971). Increased use has intensified concern that chemical retardants be used effectively and at least cost. To help the fire manager achieve these objectives, publications such as "Chemicals for Forest Fire Fighting" (National Fire Protection Association 1967) have been published. Much research remains to be done, however, to answer questions of where to apply the chemical, in what concentration, and in what form for various fire situations and fuel types. The objective is to develop enough knowledge so the fire manager can prescribe the chemical tool needed to perform a specific job of fire control at least cost.

With the increases in technology that have occurred in recent years, delivery systems for chemical retardants are receiving increased attention. Concurrently, additional effort is needed to identify the critical fuel, location of main fire hazard, and what portion of a retardant load can be expected to be delivered to that critical fuel. The retention characteristics of the forest complex must be understood well enough to estimate the volume of retardant that will be transmitted to the critical fuel.

This paper describes the results of an investigation of the effects of fuel diameter and surface roughness upon retardant retention and provides a method for estimating retardant transmission through a tree canopy.

BACKGROUND RESEARCH

A series of tests to characterize retardants (droplet size, distribution, overall pattern, etc.) dropped by various delivery systems were started at Porterville, Calif., in 1970, and are reported by George and Blakely (1973). As a substudy to the Porterville tests, the vertical distribution of retardants within arrays of 1/2-inch wooden dowels or sandblasted aluminum tubing was determined. These tests provided the base data for the study reported in this paper.

The distribution and retention of a retardant likely derives from its rheologic properties, such as cohesiveness, adhesiveness, surface tension, and viscosity, along with the droplet size and velocity at time of impact upon fuels with specific surface characteristics, including diameter. The tests at Porterville were designed to quantitatively assess the horizontal distribution of retardant dropped by an aircraft. The retardant was dropped on a network of liquid receivers that formed a matrix of interception points. Between these interception points were placed the arrays of 1/2-inch elements that provided data on the relationship of retardant transmission through several strata of uniform elements to the nature of the element. The results are summarized by George and Blakely (1973).

The retardant retained on the element was normalized (i.e., made a fraction of the quantity of retardant reaching the ground) and measured as the average of the four adjacent grid points. The fractions passing through each vertical stratum were then summed for the fuel element type--aluminum or pine dowels. Mean values for the fractional concentrations, the portion of the original amount, and for the two types of elements were determined and are given in the following tabulation:

<i>Element type</i>	C_0	C_1	C_2	C_3	C_4	C_5
Aluminum	1.000	0.922	0.844	0.764	0.708	0.654
Pine dowels	1.000	.890	.793	.691	.610	.534

where:

C_0 = concentration arriving above the strata of elements

C_1 to C_5 = fraction of concentration passing through each stratum.

Linear regression equations were determined that fit these data. The equation for the 1/2-inch aluminum elements was:

$$Y = 0.980 - 1.61X, r = 0.9955 \quad (1)$$

For the pine dowel, 1/2-inch elements:

$$Y = 0.972 - 2.15X, r = 0.9980$$

where:

Y = fraction concentration transmitted

X = element diameter $\times$ number of strata traversed

These equations describe retardant concentrations for stratum of 1/2-inch elements of the two materials, but cannot be applied to the range of fuel diameters existing in the field.

In many operational retardant drops, the retardant has significant forward velocity. Recent tests indicate the most effective ground distribution pattern is attained when the retardant is released at heights that allow dissipation of forward velocity and the formation of a true retardant cloud. Reviews of the literature through fall of rain for assistance in describing retardant transmission and retardant generated a different concept to consider. The vertical fall of rain or retardant through a tree crown is very similar to the transmission of sunlight that is attenuated by the material through which it passes. Therefore, it should be possible to apply the principles of radiant energy transmission and attenuation to retardants and rain.

We have to assume that the material is dropping vertically and has some uniform particle distribution. In addition, the total surface area of the vegetation can capture the retardant while only the frontal area blocks sunlight or radiant energy. The attenuation of radiant energy is defined by the distance traveled through the vegetation to reduce the intensity by 63 percent and is called the mean free path. This distance can be determined from the product of the surface area-to-volume ratio, σ , of the vegetation and the packing ratio, β , of the vegetation.

The equation for the amount of retardant transmitted through a stratum would have a second component to account for the part intercepted but not retained. Various investigators have considered this as part of the drainage of the canopy, storage in the canopy, and evaporation from the vegetative surfaces (Graham and Wilson 1944; Hamilton and Rowe 1949; Raymond 1967; Rutter and others 1971). The general form of the equation for retardant transmission is:

$$C_n = C_{n-1} [e^{-\sigma \beta l} + D]$$

where:

C_n = transmitted concentration through n number of strata

C_{n-1} = concentration above the stratum, n

D = fraction not retained

σ = surface area-to-volume ratio of the fuel element, ft^{-1}

β = packing ratio of the fuel array, dimensionless

l = distance into the strata, ft

This equation was applied to the data collected by George and Blakely, and the results for drop test No. 16 were used as an example. Since we knew the thickness of elements in the arrays (one-half inch) and their spacing, we therefore could set up the values to enter into the exponent of equation (3). The original concentration was known and the retardant retained by each layer was known, so the only component of equation (3) left to be determined was D.

Since each fuel array presented five discrete levels of fuel elements, the distance through a stratum was considered to be the thickness of the element, one-half inch (1.27 cm). With the spacings as cited by George and Blakely, the packing ratio, β , for each stratum would be 0.168. (Packing ratio is the ratio of fuel volume-to-stratum volume.) The surface area-to-volume ratio, σ , for 1/2-inch dowels is 96 ft²/ft³ (3.16 cm²/cm³). From the retardant data collected we know that only 10.5 percent of the retardant dropped was retained in the first stratum so that $C_n = 0.886$. Working with fractions we can now express the general equation (3) as:

$$D = 0.886 - \exp(-0.672) \quad (4)$$

Solving for D, we obtain a value of 0.359. This then can be substituted into the equation (3), and with the exponent values we can determine the decrease in retardant transmitted by layers. Of the retardant drops examined, drop No. 16 was selected as an example. The comparison is shown in the tabulation:

<i>Strata</i>	<u><i>Concentration</i></u>		<u><i>Fraction transmitted</i></u>	
	<i>G/cm²</i>	<i>Gal/100 ft²</i>	<i>Observed</i>	<i>Calculated</i>
0	0.123	2.8	1.000	1.000
1	.123	2.8	.895	.886
2	.123	2.8	.798	.780
3	.123	2.8	.702	.691
4	.123	2.8	.607	.610
5	.123	2.8	.516	.537

This analysis showed that only data about the first stratum are necessary to develop the information needed in equation (3). Therefore, a study was designed to investigate the effects of fuel size based upon only one stratum of elements. By including two different materials, we could gather additional information on effects of surface roughness and predict results of field application of retardants. Should retardant physical properties be altered so that very large droplets (3 to 5 cm) reach the fuel, retention predictions must consider momentum.

Since fire spreads fastest in fine fuels, the study was concentrated on retardant retention in fuels one-half inch or less in diameter. Enough information was known on certain brush species and timber types to determine size distributions 2 inches and under and to select a mean surface area-to-volume ratio for the fuel type. A literature search was conducted to accumulate the necessary vegetative information.

TEST PROCEDURES

Fire in tree crowns or on the ground generally occur in fine fuels; therefore, it was decided to make our test elements of a size range that would represent fuel diameters from branchwood down to conifer needles. Elements one-half inch, one-fourth and one-eighth inch in diameter were utilized to represent branchwood dimensions. Elements of 0.057-inch nylon monofilament were used to approximate conifer needles. (This is about twice the diameter of most conifer needles.) Elements were made up of one element each of the three larger fuel sizes and 10 elements of the needle size (fig. 1). Elements of white birch and polypyrolene were also used so the effect of surface roughness on retention could be evaluated.



Figure 1.--Fuel arrays of tests. In both arrays, two strands of monofilament (0.057 inch) represented conifer needles.

Ten arrays of each type of material were exposed to each of 10 retardant drops in the series of tests conducted at Marana, Arizona, early in 1972. The arrays were positioned along the flight line in the retardant measuring grid. Location of the arrays in the grid allowed the use of four adjacent retardant measurement points to establish the average concentration of retardant each array received. The arrays were placed in the grid prior to the drop, picked up immediately afterwards, and dried on holding racks. Arrays were then secured in transporting boxes and returned to the Fire Laboratory in Missoula, Montana.

The arrays were disassembled, the fuel elements oven-dried, and gross weight determined. The retardant was then washed off and the oven-dry weight redetermined to get the tare weight of the element. The difference in weight before and after drying provides the retardant weight retained by each element. Control tests were run with the white birch elements to be sure that washing did not alter weights by leaching minerals from the wood. Retardant viscosity and altitude of drop were recorded as possibly affecting retention (table 1). However, analysis of the amount of retardant on the elements as a fraction of the total delivered on a unit area basis showed no change due to retardant type or drop altitude. Therefore, the data are grouped regardless of retardant type for this series of tests.

Table 1.--Retardant retention tests using B-17 aircraft, Marana, Ariz.

Test No.	Drop No.	Date	Gallons dropped	Retardant type	Thickener	Tank viscosity
						<i>Centipoise</i>
1	3	2/1/72	500	Phos-Chek	Gum	6,300
2	6	2/2/72	500	Phos-Chek	Gum	2,300
3	8	2/2/72	500	Phos-Chek	Gum	1,700
4	10	2/2/72	500	Fire-Trol	Clay	4,900
5	15	2/3/72	500	Phos-Chek	Gum	960
6	17	2/3/72	500	Phos-Chek	Gum	1,700
7	21	2/4/72	500	Fire-Trol	Clay	1,400
8	38	2/9/72	2,000	Phos-Chek	Gum	1,675
9	47	2/10/72	500	Fire-Trol	Undiluted liquid concentration	1,900
10	51	2/10/72	500	Petro-Lite	Emulsion	>10,000

TEST RESULTS AND ANALYSIS

The concentrations of retardants within each grid point were taken from the gallons per 100 square feet (gal/100 ft²) tabulations and equated to the measurements for the elements in g/cm² or lb/ft². Because of steep gradients in retardant concentration patterns, the amount of retardant retained by elements varied greatly within a drop. To normalize the results, weight of retardant retained by the element was divided by weight of retardant received on the ground. These values are summarized in table 2.

Table 2.--Fractional retention of retardant by fuel size (lb/ft² total sample area : lb/ft² ground surface area)

Drop No.	Polypyrolene element size (inch)				White birch element size (inch)			
	0.50	0.25	0.125	0.057	0.50	0.25	0.125	0.057
3	0.350	0.361	0.313	0.339	0.260	0.302	0.060	0.406
6	.208	.376	.255	.244	1.000	.058	.000	.000
8	.316	.323	.241	.257	.950	.017	.000	.000
10	.165	.177	.238	.068	1.000	1.000	.000	.000
15	.169	.211	.141	.123	.642	.416	.000	.000
17	.186	.225	.178	.140	1.000	.000	.000	.000
21	.234	.247	.211	.077	.700	.482	.000	.000
38	.103	.123	.107	.086	.426	.100	.101	.000
47	.281	.319	.193	.088	.416	.000	.195	.000
51	.313	.357	.191	.259	1.000	.000	.000	.000
$\bar{X}$	.232	.271	.207	.168	.747	.620	.441	.000

¹ The smallest-diameter element (0.057 inch) on both white birch and polypyrolene arrays is monofilament nylon line.

The data of table 2 were subjected to Student's "t test" of the mean, and at the 99-percentile point the value of t for 18 degrees of freedom had to exceed 2.55 to indicate a significant difference between the elements. All of the elements except those of 0.057-inch diameter common to both sets of arrays had significant differences, as shown below:

<i>Size</i> <i>Inch</i>	<i>t value</i>
0.50	5.42
.25	3.25
.125	2.75
.057	0.22

Because the smallest size, the monofilament line, common to both arrays, had no significant difference, it is assumed that placement of the arrays on the matrix did not introduce bias and all of the data for this smallest size were lumped. Because of surface roughness, this size was considered with the polypyrolene data. The summary of the fraction retained by size, Y, is given in the following tabulation:

<i>Element type</i>	<i>Element size (inch)</i>			
	<i>0.50</i>	<i>0.25</i>	<i>0.125</i>	<i>0.057</i>
Polypyrolene	0.2324	0.2708	0.2066	0.1717
White birch	.7473	.6202	.4411	

These data were then analyzed for equations of best fit. The exponential equation found to give the closest fit for both types of elements was of the general form:

$$Y = B \exp(-A \times \sigma) \quad (5)$$

where:

Y = the fraction retained
 σ = surface area-to-volume ratio
A & B = constants

The values of the constants for the two element types and the correlation coefficient are given in equations (6) and (7):

$$\text{Polypyrolene: } Y = 0.264 \exp(-5.5 \times 10^{-4} \times \sigma) \quad (6)$$

$$r = 0.8870$$

$$\text{White birch: } Y = 0.885 \exp(-1.83 \times 10^{-3} \times \sigma) \quad (7)$$

$$r = 0.9997$$

These data, graphically presented in figure 2, show the difference in retention according to surface roughness. As the surface area-to-volume ratio approaches 900 (less than 0.125 inch in diameter), the retention capabilities fall below 0.20, and possibly merge. This suggests small-diameter fuels have about the same retention ability regardless of surface roughness.

These equations do provide a means for estimating retardant retention within fuel complexes that have mean surface area-to-volume ratios represented by these data. We assumed that the white birch curve is a good simulation for most branchwood of conifers, and the curve for polypyrolene is a good simulation for foliage and for branchwoods that have smooth surfaces or have a high oil content. To use any of these equations for determining the retardant delivered to a critical fuel, we must have detailed knowledge of the vegetative medium through which the retardant travels, including the vertical arrangements of the vegetation.

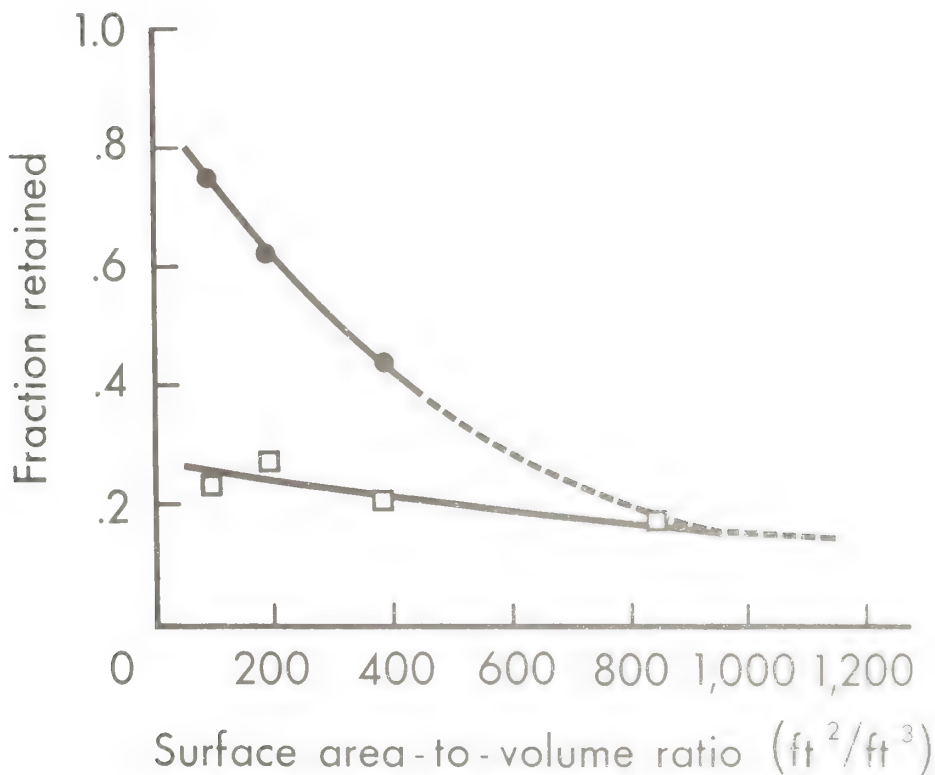


Figure 2.--Differences in retardant retention because of surface roughness (● white birch and ■ polypropylene) plotted against the surface area-to-volume ratio or fuel diameter.

Information reported by George and Blakely (1973) and results of this study provide enough data to illustrate how four different surface textures affect retention. The retention factor from figure 2 for the 1/2-inch white birch applied to the packing ratio of the array used by George and Blakely indicates the retardant retained per stratum. The amount of retardant retained by one layer of 1/2-inch elements should be 0.1255. With the use of equation (3) we can arrive at values for the drip-through factor, D, as shown previously. The values for D with 1/2-inch elements can be compared for two separate tests.

It was found that the white birch and pine dowel 1/2-inch elements had approximately the same D factor, followed by aluminum tubing and polypyrolene tubing, in the following tabulation:

Element type	"D" factor
White birch	0.3633
Pine dowels	.3780
Aluminum tubing	.4107
Polypyrolene	.4456

We can see that as surface roughness changes, the amount of retardant retained changes, white birch being most rough and polypyrolene least rough. However, since we do not have measurements to adequately describe surface roughness for the different timber types, species of vegetation, or to relate these to the timber roughness

This information will see limited application until additional surface roughness data are obtained; however, the relationship of retention to roughness can be illustrated by plotting retardant transmission through a five-layered array (fig. 3). It is evident that surface roughness can change up to 1-1/2 times the quantity of retardant reaching an area. Roughness of the surface is only one of the variables affecting retardant retention. The surface materials' properties such as porosity, chemical composition, and specific gravity may have an effect. The retardant itself may have differences in cohesiveness, surface tension, density, or viscosity that significantly alter retention. However, the effort needed to obtain the information must be established by the level of use in field operations.

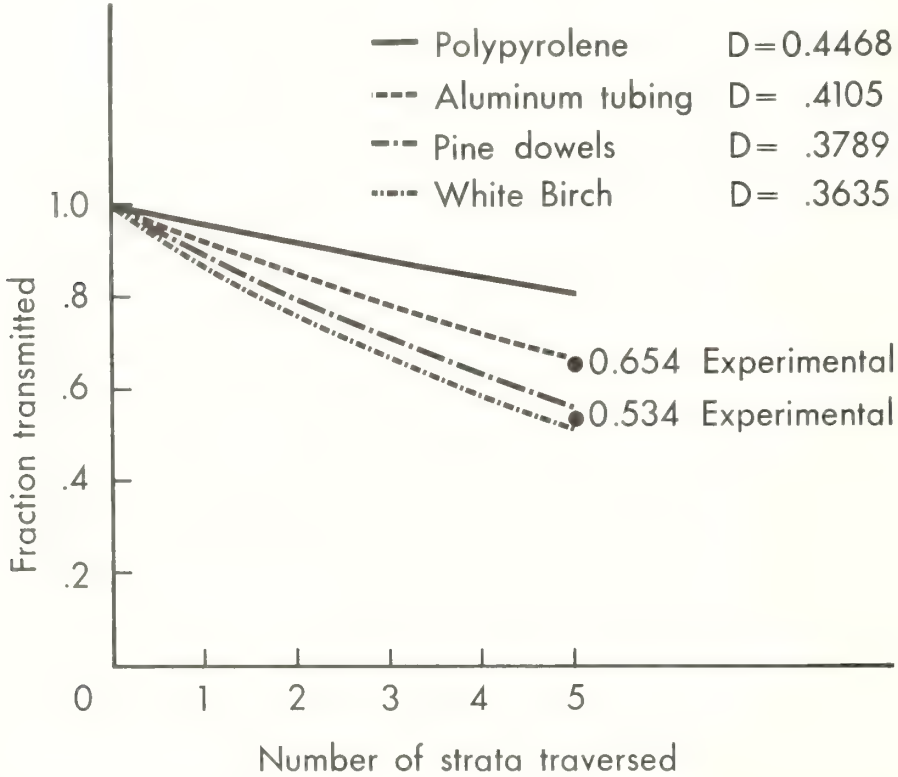


Figure 3.--Computed amounts of retardant transmitted through several layers of fuel or vegetation having different surface roughness. Fraction transmitted can be changed by the surface roughness. The experimental points show the agreement with results for pine dowels and aluminum tubing by equation (3).

APPLICATION

Efforts to develop more effective retardant delivery systems have made it mandatory that we know what portion of the retardant reaches those fuels most apt to carry fire. Assuming the fire-carrying fuel strata will be on the ground, retardant must be transmitted down through an overstory to reach those ground fuels. Because crown fuels can carry fire under specific conditions, it may also be desirable to retain as much retardant as possible in the crown material. In brushfields, the overstory shelters the understory of dead branchwood, leaf litter, and annual vegetation debris. In coniferous forests, tree canopies will shield the litter layer and brush story that may carry the fire. To estimate how much retardant needs to be delivered above a canopy, we have to determine the attenuation or retention of retardant passing through these various strata. Review of the literature shows that most investigators have considered the crown, or canopy, to be a homogeneous mixture of vegetation and branchwood.

The point of maximum fuel within the crown height has been observed and differences by species, age, or growth condition recorded (Mar:Moller 1947; Baskerville 1965; Kiil 1967; Smith 1968; Stephens 1969; Honer 1971; Moir and Francis 1972). These investigations and others provide valuable insights into the biomass distribution and other crown characteristics. To evaluate retardant transmission, however, it is necessary to know the quantity of foliage, its size and shape, the distribution of branchwood in the crown, and also the foliage and branchwood spatial location. Although little information has been published, we do have enough data for western conifers to indicate what can be done. The work by Storey and associates (1955) and by Fahnestock (1960) contains the information necessary to estimate the branchwood and foliage distribution within the crown. However, quantifying crown characteristics requires a geometrical shape for both the foliage and branchwood zones.

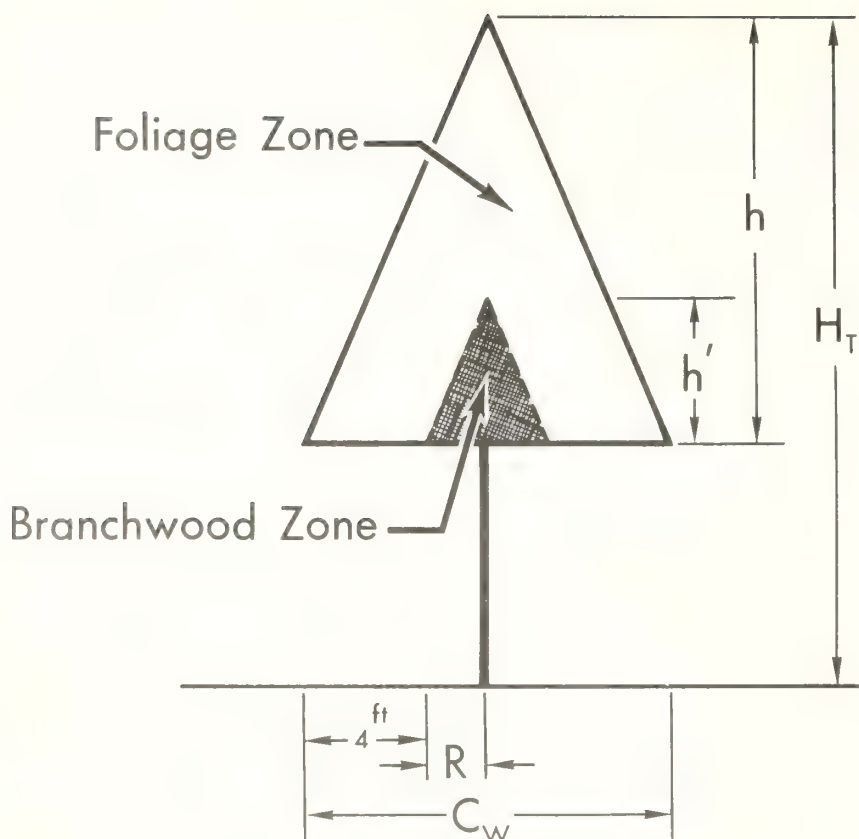


Figure 4.--Model used to develop equations describing physical properties of the crown. Symbols are defined in the text.

For the purpose of this paper we will use the data available for inland Douglas-fir and utilize the equations developed by Brickell (1968) to indicate the changes due to site and age. The configuration of a tree crown is assumed to be conical and have an outer foliage zone surrounding a branchwood zone. The foliage envelope thickness is considered to extend 4 feet horizontally and to include all foliage and all branchwood material up to one-half inch in diameter. The inner cone of branchwood is considered to contain only material greater than one-half inch in size. The general crown concept is shown in figure 4.

Having established dimensions of the tree crown, either from equations or by assumed values, we can now calculate the physical dimensions of the branchwood zone, along with the foliage zone based upon the volume of a cone. To illustrate the retardant retention equations, along with the equations describing crown envelopes, we use Brickell's inland Douglas-fir values on a site of 60 (50-year basis) at ages 20, 50, and 100 years.

$$H_T = 91.57[1 - 1.153e^{-0.0255A}]^{1.0608} = \text{tree height, ft} \quad (8)$$

where A = age, years

$$DBH = \exp[1.317 \ln H_T - 2.688] = \text{diameter, inches} \quad (9)$$

These equations are used as inputs to the following equations:

$$h = 4.0 + 2.60 \text{ DBH} = \text{crown length, ft} \quad (10)$$

$$W_c = \frac{[(DBH)(h)]^{1.0108}}{3.811} = \text{crown weight/tree, lb/tree} \quad (11)$$

These equations were determined by Fahnestock, or were modified by him after Storey:

$$C_w = 5.031 + 1.423(\text{DBH}) = \text{maximum crown width, ft} \quad (12)$$

This equation is cited by Bella (1971) and is taken from data acquired by Newnham.¹ This equation may not represent inland Douglas-fir as accurately as coastal Douglas-fir.

Using the assumptions made for crown geometry, we can formulate the equations for the radius and the height of the branchwood zone.

$$R = 0.5 C_w - 4 = \text{base radius of branchwood zone, ft} \quad (13)$$

$$h' = \frac{(h)(R)}{0.5C_w} = \text{height of branchwood zone, ft} \quad (14)$$

The work by Storey on western conifers provides total crown weight and the portion that is in foliage and branchwood.

$$w_f = 0.235 W_c, \text{ foliage weight/tree, lb} \quad (15)$$

$$w_h = 0.765 W_c, \text{ branchwood weight/tree, lb} \quad (16)$$

This information is then coupled with the work by Fahnestock to define the fraction of branchwood in the foliage zone and set up equations:

$$W_f = w_f + 0.244 w_h = \text{foliage zone weight, lb} \quad (17)$$

$$W_h = 0.756 w_h = \text{branchwood zone weight, lb} \quad (18)$$

A range of fuel diameters, or size classes, exists in both zones and retardant transmission is affected by each size class in each zone. To estimate the summed effect of size on transmission in each zone, a mean (or characteristic size of elements in each zone) is computed. This is accomplished with data on the crown weight proportioning and surface area distribution in the two zones. The data from Storey and from Fahnestock are consolidated to give the mean surface area-to-volume ratio for each class and the portion of the total crown load that was in each class. They are as follows:

Zone	Size Class (inches)	Surface area-to-volume ratio, σ	Weight, lb
Foliage	<1/8	2,100	770
	1/8 - 1/4		256
	1/4 - 1/2		128
	1/2 - 1		64
Branchwood	1 - 2		32
	>2		18
			0

¹R. M. Newnham. Unpublished thesis. University of British Columbia. 1964.

The mean surface area-to-volume ratio for the foliage zone was determined by weighting by surface area because the total surface area may be active in retaining retardant. The mean surface area-to-volume ratio of the foliage is determined by equation (19) and for the branchwood zone by equation (20).

$$\bar{\sigma}_s = \left[\frac{w_1 \sigma_1}{\rho_1} + \dots + \frac{w_4 \sigma_4}{\rho_4} \right] \div \left(\frac{W_c}{\bar{\rho}} \right) = \begin{array}{l} \text{mean surface-to-area} \\ \text{volume, ft}^2/\text{ft}^3 \text{ of} \\ \text{foliage zone} \end{array} \quad (19)$$

where:

$w_1 \dots$ = fraction of crown weight in size class

W_c = crown weight

ρ_1 = density of size class

$$\bar{\sigma}_b = \left[\frac{w_5 \sigma_5}{\rho_5} + \frac{w_6 \sigma_6}{\rho_6} \right] \div \left(\frac{W_c}{\bar{\rho}} \right) = \begin{array}{l} \text{mean surface area-to-volume} \\ \text{of branchwood zone, ft}^2/\text{ft}^3 \end{array} \quad (20)$$

The volume of each zone is then calculated, using equations for a cone:

$$V_b = 1/3\pi R^2 h' = \text{branchwood zone volume, ft}^3 \quad (21)$$

$$V_F = 1/3\pi(0.5C_w)^2 h = V_b = \text{foliage zone volume, ft}^3 \quad (22)$$

These equations allow us to estimate bulk densities for each zone, their volume, and the vertical distance through the zones at varying distances from the bole of the tree. In addition, we can compute the probable total surface area, in both the foliage and branchwood zones, and estimate the storage capacity of the crown by following the research done for precipitation throughfall (Grah and Wilson 1944; Hamilton and Rowe 1949; Raymond 1967; and Rutter and others 1971). Storage capacity has been defined by Grah and Wilson as the theoretical depth to which water would be retained if spread evenly over the plant surfaces. They calculated values of 0.003 and 0.007 inch, respectively, for *Pinus radiata* and *Baccharis pilularis*. Comparable values were reported by Leyton and others (1967): film thicknesses from 0.003 to 0.008 inch for grasses and some trees, and values up to 0.015 inch for bracken.

The amount of retardant retained in a tree canopy will be affected by the viscosity, cohesiveness, adhesiveness, or other rheological retardant properties, and until experimental results indicate a better value we will assume a theoretical depth (film thickness) of 0.007 inch. By applying the equations and the assumed liquid depth we can compute the retardant drop concentration that would saturate the crown. For a 50-year-old tree this was found to be 2.44 gal/100 ft² of ground area or 0.039 inch of liquid per square foot of projected crown area. This is less than the 0.05 inch cited by Zinke (1967) as storage capacity for rain on most grasses, shrubs, and trees. The computed value, however, is certainly within the range of observed storage capacities.

When precipitation or retardant falls, the storage capacity starts to be filled, but a certain portion of the liquid passes through the crown to the ground as throughfall. The amount of throughfall can be estimated by using equations for the crown property with the results of the retardant retention equations discussed earlier. For the foliage zone, equation (6) for polypyrolene represents the surface retention property:

$$Y = 0.264 \exp(-5.5 \times 10^{-4} \times \bar{\sigma})$$

With a mean surface area-to-volume ratio, $\bar{\sigma}$, of 1,074 ft²/ft³, the retardant fraction retained, Y, equals 0.125. For the branchwood zone, the white birch equation (7) represents the retention characteristic:

$$Y = 0.885 \exp(-1.83 \cdot 10^{-4} \cdot \bar{\sigma})$$

With a mean surface area-to-volume ratio of 45.3 ft²/ft³, the retardant fraction retained equals 0.822. The crown properties of three ages of trees are given in table 3.

These data can be combined to describe the transmission of retardant through a tree crown and the distribution on the ground. To study retardant retention by size class, we made the following assumptions: (1) The retardant is dropped from a high enough altitude so its forward velocity is zero before reaching the fuel; (2) all of the crown surface area is available to retain retardant; (3) the retardant is uniform in droplet size; and (4) attenuation is similar to that affecting radiant energy transmission. In addition, the drip-through component is not considered because the rheologic properties of retardants introduce numerous unknowns affecting drip-through. The general form of equation (3) is then reduced to:

$$C_n = C_{n-1} \exp(-\gamma \sigma \beta l)$$

However, we refine this equation by introducing the two strata--foliage and branchwood zones--and the retardant fraction retained, Y, becomes γ_f and γ_b for each zone.

$$C_n = C_{n-1} [\exp(-\gamma_f \sigma_f \beta_f l_f)] [\exp(-\gamma_b \sigma_b \beta_b l_b)]$$

where:

subscripts f and b refer to foliage and branchwood, respectively

σ_f and σ_b = mean surface area-to-volume ratio, ft²/ft³

β_f and β_b = packing ratio, dimensionless

l_f and l_b = distance through the zone, ft

γ_f and γ_b = retardant capture effectiveness, dimensionless.

The vertical distances through the two zones of a tree canopy can be calculated for any given radius from the bole and the other three values of the exponent for both zones are known; therefore, the fractional amount of retardant transmitted through canopies can be calculated. Figure 5 shows the distribution underneath the canopies for the trees shown in table 3. The sharp breaks occurring for the 20- and 100-year-old trees illustrate that data are lacking on the changes in weight of foliage and branchwood that occur with age and variations in thickness of the foliage zone.

The degree of agreement between the concept of transmission and the natural situation is illustrated by the comment made by Eschner (1967): "Delfs (1958) showed a pattern of throughfall under spruce increasing in the following order: mature stand, pole stand, saplings and regeneration." The distribution underneath 100-, 50-, and 20-year-old fir shown in figure 5 agrees with this observation. Results of this study can also be tested by the work of Zinke (1967) and Stout and McMahon (1961), who presented data for hardwoods and conifers in spring conditions and throughfall distribution at various distances out from the bole to the perimeter of the tree crown. The points between the bole and the perimeter were normalized by the radius of the crown, and the results obtained from this study were compared to observed values (1961).

The modeling tends to predict greater interception than actually found. Since the equation for throughfall of retardant does not allow for drip-through and transport other than direct vertical fall, we would expect that there would be more retardant actually transmitted than predicted.

Table 3.--Crown characteristics calculated for Douglas-fir at three ages

Properties of tree	Age in years		
	20	50	100
Total height, H_T (feet)	26.2	60.6	82.8
Diameter, DBH (inches)	5.0	15.1	22.9
Crown height, h (feet)	17.1	43.4	63.4
Crown weight, W_c (pounds)	23.6	185.0	412.0
Crown width, C_w (feet)	12.2	26.6	37.6
Branchwood zone:			
Height, h' (feet)	5.9	30.3	49.9
Radius, R (feet)	2.1	9.3	14.8
Surface area-to-volume, σ (ft ² /ft ³)			
Foliage zone	1,074.0	1,074.0	1,074.0
Branchwood zone	45.3	45.3	45.3
Packing ratio, β (dimensionless)			
Foliage zone	4.5×10^{-4}	4.3×10^{-4}	4.2×10^{-4}
Branchwood zone	1.5×10^{-2}	1.1×10^{-3}	6.0×10^{-4}

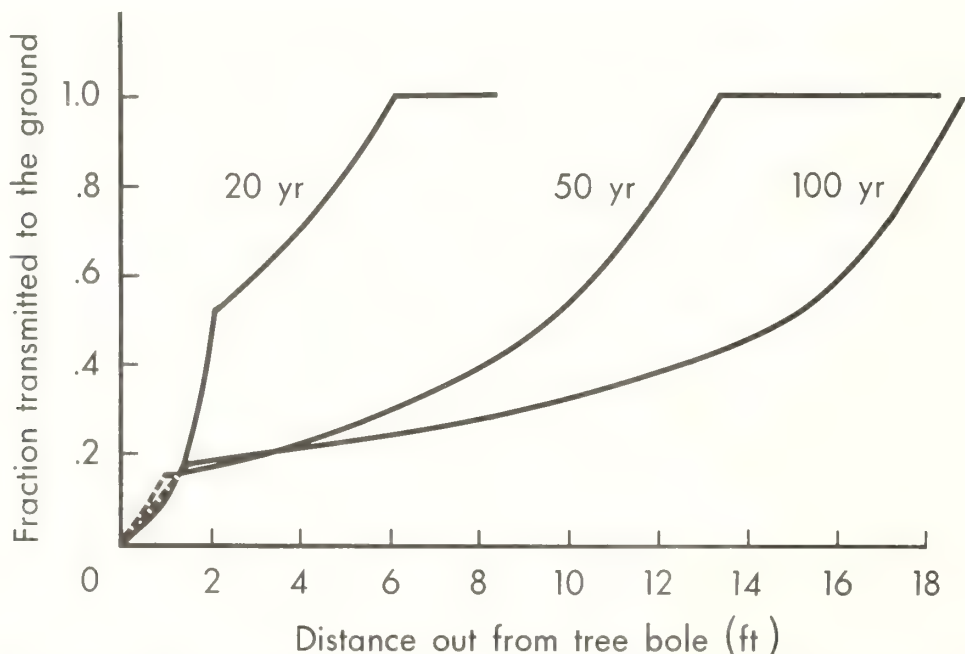


Figure 5.--Retardant transmission through crowns of trees of three different ages. Fraction reaching ground appears to become less as tree ages.

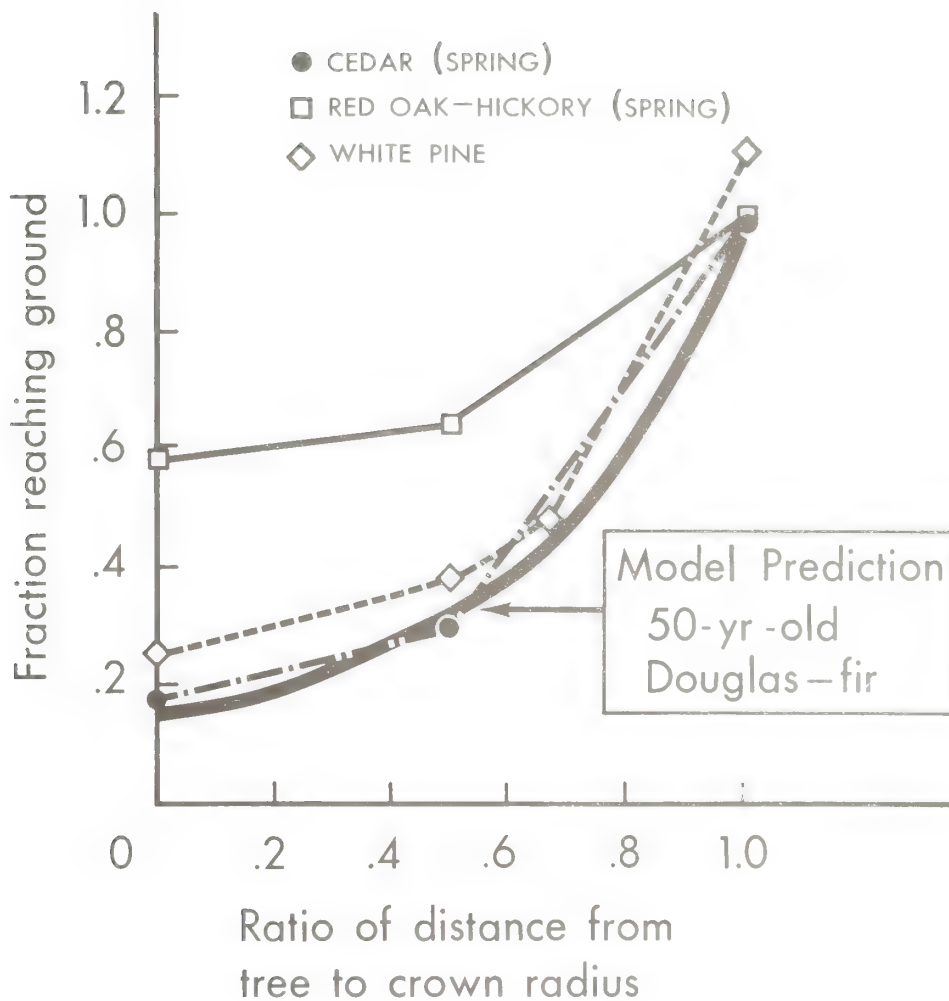


Figure 6.--Retardant throughfall predicted by modeling (Douglas-fir) compared to rain throughfall (cedar, red oak, white pine) reported by others. Fractions reaching ground are similar.

CONCLUSIONS

The results of the retardant drop tests provided equations that relate retardant retention to fuel size. In addition, the influence of surface roughness could be identified. Droplet size, which was observed to be a function of rheological properties, was not part of the study. Additional studies should be made to account for rheologic variations, such as the effects of viscosity or other rheologic properties on droplet size and spatial distribution within the retardant cloud.

Applying tree crown data has illustrated the types of distribution that can be expected under tree canopies. The results agree with recorded field observations. Results among different timber types cannot be compared until additional information is acquired on the relationships between foliage and branchwood within tree canopies for the various western conifers by age, site, and aspect. Additional work is needed to define changes in the foliage zone with age and condition of the tree. Work also is needed for stand conditions where crown data for open-grown trees do not fit.

Distribution of trees within a stand needs to be studied so we can realistically assess retardant distribution on the ground under various crown closure conditions. From this information it will be possible to estimate retardant penetration and predict degree of penetration through tree crowns. In addition, the information acquired may prove valuable to other modeling efforts such as predicting crown fires.

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ANALYSIS, PAGE 1

1. The first step in the analysis is to identify the main components of the system. In this case, the components are the input, the process, and the output. The input is the data provided by the user, the process is the algorithm that processes the data, and the output is the result of the process.

2. The second step is to analyze the input. This involves identifying the data types and the range of values. For example, if the input is a list of numbers, we need to know if the numbers are integers or floating point numbers, and if they are within a certain range.

3. The third step is to analyze the process. This involves identifying the steps of the algorithm and the data structures used. For example, if the algorithm uses a loop, we need to know if it is a for loop or a while loop, and if it uses an array or a linked list.

4. The fourth step is to analyze the output. This involves identifying the data types and the range of values. For example, if the output is a list of numbers, we need to know if the numbers are integers or floating point numbers, and if they are within a certain range.

ANALYSIS, PAGE 2

5. The fifth step is to analyze the overall system. This involves identifying the main components and how they interact. For example, if the system is a database, we need to know if it uses a relational database or a non-relational database, and if it uses a client-server architecture or a peer-to-peer architecture.

6. The sixth step is to analyze the performance of the system. This involves identifying the factors that affect performance, such as the amount of data, the complexity of the algorithm, and the hardware used. We need to know if the system is fast enough for the intended use.

7. The seventh step is to analyze the security of the system. This involves identifying the threats to the system and the measures to protect it. For example, if the system is a database, we need to know if it is protected by a firewall and if the data is encrypted.

8. The eighth step is to analyze the maintainability of the system. This involves identifying the factors that affect maintainability, such as the complexity of the code and the documentation. We need to know if the system is easy to maintain.

ANALYSIS, PAGE 3

9. The ninth step is to analyze the scalability of the system. This involves identifying the factors that affect scalability, such as the amount of data and the number of users. We need to know if the system can handle more data and more users.

10. The tenth step is to analyze the flexibility of the system. This involves identifying the factors that affect flexibility, such as the ability to add new features and the ability to change the configuration. We need to know if the system is flexible enough for the intended use.

11. The eleventh step is to analyze the reliability of the system. This involves identifying the factors that affect reliability, such as the availability of the hardware and the robustness of the code. We need to know if the system is reliable enough for the intended use.

12. The twelfth step is to analyze the cost of the system. This involves identifying the factors that affect cost, such as the hardware and the software. We need to know if the system is cost-effective for the intended use.

ANALYSIS, PAGE 4

13. The thirteenth step is to analyze the user interface of the system. This involves identifying the factors that affect the user interface, such as the ease of use and the visual appeal. We need to know if the user interface is user-friendly.

14. The fourteenth step is to analyze the documentation of the system. This involves identifying the factors that affect the documentation, such as the completeness and the clarity. We need to know if the documentation is good enough for the intended use.

15. The fifteenth step is to analyze the support of the system. This involves identifying the factors that affect the support, such as the availability of the support team and the quality of the support. We need to know if the support is good enough for the intended use.

16. The sixteenth step is to analyze the future of the system. This involves identifying the factors that affect the future, such as the technology and the market. We need to know if the system has a good future.

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♂ *Arceuthobium douglasii*



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ECOLOGY OF DWARF MISTLETOE SEED

Ed F. Wicker



USDA Forest Service
Research Paper INT-154, 1974

INTERMOUNTAIN FOREST &
RANGE EXPERIMENT STATION
Ogden, Utah 84401

ECOLOGY OF DWARF MISTLETOE SEED

Ed F. Wicker

This study is based on a portion of a thesis submitted in partial fulfillment of the requirements for the Ph.D. degree, Department of Plant Pathology, Washington State University. (Scientific Paper 4152, College of Agriculture Research Center, Washington State University, Pullman, Project 1490.) This work was supported in part by funds provided for biological and medical research by the State of Washington Initiative No. 171, and by the USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah.

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U. S. Department of Agriculture
Ogden, Utah 84401
Roger R. Bay, Director

THE AUTHOR

ED F. WICKER, Plant Pathologist, is assigned to Research Work Unit INT-2303, Forestry Sciences Laboratory, Moscow, Idaho. He is responsible for research investigations on the biology and ecology of forest tree diseases. Dr. Wicker joined the Intermountain Station staff in 1956. He received the Bachelor of Science degree in forestry (1959) and the Doctor of Philosophy degree in plant pathology (1965) from Washington State University. He is recognized as a specialist on the biology, ecology, and control of dwarf mistletoes and biological control of forest tree diseases. During 1970-1971, he was on a 1-year work assignment in Europe to investigate biological control agents for the blister rust disease of white pines. Dr. Wicker received a Japanese Government Research Award in 1974 for 6 months' work on rusts of white pines in Japan.

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ABSTRACT

Information on seed viability, germinability, dormancy, and longevity for several species of Arceuthobium is presented and methods for testing these qualities during storage are described. Data on the effects of temperature, relative humidity, and light on seed vitality are reported. Some mold fungi capable of reducing the vitality of dwarf mistletoe seed are identified.

INTRODUCTION

Experimental investigations of dwarf mistletoes (*Arceuthobium* spp.) that involve mass artificial inoculations require large amounts of seed. Fruit of the species discussed in this paper mature in September-October and seed are cast by an explosive fruit mechanism. Thus, it is most convenient and practical to collect the seed at this time (Wicker 1967a).

Unless seed are to be used immediately after collection, maximum germinative capacity must be maintained in storage. Consequently, storage practices can be evaluated only in terms of net effect upon the physiological condition of seed as represented by seed viability, germinability, longevity, and dormancy. These attributes are influenced by such environmental factors as seed moisture content, oxygen supply, temperature, light, relative humidity, and time, as these relate to the quality and rate of respiration.

When my studies were initiated, investigation of many aspects of the biology of dwarf mistletoes in controlled experiments was difficult, if not impossible, because of insufficient knowledge of seed ecology. Successful artificial inoculations were possible only during September-October when seed were being cast, and then only within natural environments. Even so, success was low, seldom exceeding 5%. Most available information relating to seed physiology and ecology was fragmented, general, and largely empirical (Peirce 1905; Heinricher 1915a, 1915b, 1917; Palhinha 1942; Weir 1918). Reliable methods of seed storage and of testing viability or germinability were not available; consequently, little was known about longevity and dormancy.

Previously, I reported practical methods for collecting and storing dwarf mistletoe seed (Wicker 1967a). In the current report, I present information on viability, germinability, dormancy, and longevity of seed of several *Arceuthobium* taxa. If this information is utilized, germinable seed can be available throughout the year for cultural studies.

Coincidental with my studies, Scharpf and Parmeter (1962) and Beckman and Roth (1968) were conducting similar investigations with *Arceuthobium campulopodum* Engelm.

SEED VIABILITY

Materials and Methods

A total of 71 naturally dispersed seed of *A. campylopodium* were collected from the foliage and branches of *Pinus ponderosa* D. Don near Spangle, Wash., in November. Only seed that appeared normal were collected; molded, shriveled, or discolored seed were discarded. In the laboratory, seed were presoaked in distilled water at 22°C for 24 h and then were used for the initial evaluation of 2,3,5-triphenyl tetrazolium chloride (TTC) as a viability test (Flemion and Poole 1948; Lakon 1949, 1954; Smith 1951; On 1952; Parker 1953; Grano 1958; Scharpf and Parmeter 1962). The test solution was prepared by dissolving 100 mg of TTC in 100 ml of de-ionized water.

The presoaked seed were placed in small glass vials containing the TTC test solution. The vials were capped and kept at room temperatures (22-23°C), dark for 3 days. At that time seed were removed from the test solution, excised longitudinally, and the embryo examined for red coloration indicating viability. Any red staining of the embryo was read as a positive (viable) test.

Following this initial test with naturally dispersed seed, the same procedure was used to test laboratory stored seed. Sample lots of 100 seed from each of six *Arceuthobium* taxa that had been in dry, cold, laboratory storage (5°C, 35-45% RH, dark; Wicker 1967a) for 60 days and comparable sample lots of seed stored at room air temperature and room light for 60-67 days were tested. All laboratory stored seed were collected in September and October at the locations reported by Wicker (1965).

Seed of *A. laricis* (Piper) St. John were used in a test to compare the efficacy of 0.1% ethanolic TTC with the 0.1% aqueous TTC. Six lots of 50 seed each were removed from dry, cold, laboratory storage (76 days); three lots were treated with aqueous TTC and three lots with ethanolic TTC. This test was repeated with two lots of 50 seed each of *A. campylopodium* and *A. laricis* following 86 days of dry, cold storage.

Results

Data from the preliminary test using naturally dispersed seed of *A. campylopodum* were very encouraging. Sixty-three of 71 seed (88.7%) showed a positive reaction to TTC.

Results of the test using seed of six taxa of dwarf mistletoe that had been in dry, cold, laboratory storage for 60 days are shown in table 1. These results are very favorable for the viability test and for this particular laboratory storage method.

The results with seed that had been stored at room temperature for 60 days were all negative; no red coloring of the embryo. A second test conducted 7 days later also yielded negative results.

The next test employed *A. laricis* seed that had been in dry, cold, laboratory storage for 76 days. The three lots of 50 seed each treated with the aqueous test solution showed 94%, 88%, and 92% viability; results of the ethanol treatment were all negative.

The results of tests after 86 days of dry, cold, laboratory storage verified the previous test. The seed of *A. laricis* treated with the aqueous test solution showed 94% viability, while the results of the ethanol test solution were again negative. The seed of *A. campylopodum* showed 92% viability when the aqueous test solution was used and zero percentage when the ethanol test solution was used.

Table 1.--Seed viability as determined by 2,3,5-triphenyl tetrazolium chloride after 60 days of dry, cold, laboratory storage

Dwarf mistletoe (<i>Arceuthobium</i>)	Viability ¹
	%
<i>A. abietinum</i> Engelm. ex Munz	90
<i>A. americanum</i>	76
<i>A. campylopodum</i>	92
<i>A. douglasii</i>	91
<i>A. laricis</i>	94
<i>A. tsugense</i>	87

¹Based on 100 seed per test.

SEED GERMINATION

Materials and Methods

Petri plates (15 by 90 mm) containing three discs of filter paper (9 cm) were normally employed as germinators. The germinators were sterilized by dry heat for 4 h at 185°C. The filter paper in some germinators was saturated with sterile distilled water; in others it was dry except for moisture in the saturated external viscum on the seed. These germinators are referred to hereafter as "wet" and "dry."

All seed had been in dry, cold, laboratory storage for 100-150 days prior to the germination tests. Unless otherwise stated, (1) all seed were presoaked 18-24 h in sterilized distilled water prior to other treatment and prior to being placed in germinators, and (2) all series of tests were run in duplicate--one in wet germinators, the other in dry germinators. Wet germinators were checked periodically; when seed and filter paper appeared to be dry, sterile distilled water was added until free water was evident in the plates. Tests were run at 5°, 10°, 15°, 20°, and 25°C, at room temperature (22°-23°C), and at "greenhouse temperatures" (ambient). Tests were conducted in the light and in the dark. Complete darkness was not insured, because other workers used the incubators and seed were exposed to room light when incubator doors were open. Percentage germination was determined after 40-111 days.

Some seed received additional pretreatments with various chemicals for surface sterilization or with enzymes to decompose the external viscum. All pretreatments itemized below were performed at room temperatures in the laboratory:

1. Five minutes in 95% ethyl alcohol followed by two 3-min rinses in sterile distilled water.
2. Five minutes in 6% NaClO (full strength Chlorox) followed by two 3-min rinses in sterile distilled water.
3. Two hours in 6% HCl solution (84 ml water plus 16 ml. of 37% HCl, reagent grade) followed by a 10-min rinse in sterile distilled water.
4. Two hours in a 16% H₂SO₄ solution (84 ml water plus 16 ml of 96% H₂SO₄, reagent grade) followed by a 10-min rinse in sterile distilled water.

5. Three minutes in 95% ethyl alcohol, 3 min in 6% NaClO, then 5 min in sterile distilled water.

6. Thirty-six and 72 h in a pectinase solution (500 mg pectinase/10 ml water) followed by a 5-min rinse in sterile distilled water.

7. Thirty-six and 72 h in a hemicellulase solution (500 mg hemicellulase/10 ml water) followed by a 5-min rinse in sterile distilled water.

Other chemicals and organic materials were employed in attempts to stimulate seed germination. Some seed were soaked for 5 days in an aqueous extract from Douglas-fir bark and others for 5 days in a horse dung infusion. The seed were incubated in the laboratory (10°C, 38-46% RH, dark) and in the greenhouse at ambient temperatures.

Paired seed lots were treated with dimethyl sulfoxide (DMSO) for various periods of time ranging from 30 min to 4 h. One seed lot received a posttreatment rinse in water for 30 min; the other lot for 1 h. The seed were then placed in dry petri plate germinators and stored in a growth chamber (10°C, 35-55% RH, dark) for the germination period.

Seed were treated for 5 h in 12.5% to 100% solutions of ethylene chlorohydrin, a bud-forcing chemical (Denny 1926a, 1926b; Kotowski 1926; Vacha and Harvey 1927; Deuber 1932). Upon removal from the solutions, seed were placed into dry petri plate germinators and stored in an incubator at 10°C, 35-45% RH, dark. An untreated control was similarly incubated.

The effect of hydrogen peroxide (H₂O₂) (Miège 1908; Leggatt 1929; Parker and Hill 1955; Ching and Parker 1958; Ching 1959) on dwarf mistletoe seed germination was evaluated. *Arceuthobium laricis* seed were removed from dry, cold, laboratory storage (150 days), pretreated 12-24 h with sterile distilled water, then placed in small vials containing aqueous H₂O₂, and sealed. Seed remained in the solutions for the germination period (10 days). Five different concentrations of H₂O₂ were tested at room temperatures under both light and dark conditions.

Following the initial test of the effects of H₂O₂ on *A. laricis* seed germination, the germinative capacities of seed of eight dwarf mistletoe taxa were subsequently tested. Seed were removed from dry, cold, laboratory storage (30-165 days), pretreated with sterile distilled water (18-24 h), and treated in 3% H₂O₂ at room temperature under typical laboratory light conditions.

Additional dwarf mistletoe seed were then tested with 3% H₂O₂ to determine whether or not the distilled water pretreatment was influencing the stimulatory action of H₂O₂.

The H₂O₂ (3%) germination test was compared with the aqueous TTC viability test on *A. americanum*, *A. campylopodum*, and *A. laricis* seed. Tests were run in triplicate following the same procedures outlined for the initial tests with *A. laricis* seed.

Hydrogen peroxide (3%) was used to investigate the effect of aqueous TTC on dwarf mistletoe seed. Seed were removed from dry, cold (5°C, 35-45% RH, dark) storage and soaked for 20 h in distilled water. Fifty seed each of *A. campylopodum* and *A. laricis* were put in the 0.1% TTC solution and 50 seed (controls) of each taxon were placed in distilled water. All seed were kept in the dark at room temperature. After 3 days, the seed were removed from these solutions, placed in 3% H₂O₂, and kept in the dark at room temperature for 10 days, at which time they were observed for germination.

Growth substances were also used in germination tests (Crocker 1948; Crocker and Barton 1957). Samples of 100 seed each were placed in thiamine chloride, glutathione

(1 mg/100 ml water), and ripe coconut milk and left (5°C, dark) in these solutions for 70 days.

Another technique involved submerging seed in water for the entire germination period. Three hundred and seven seed of *A. laricis* that had been in dry, cold, laboratory storage for ca. 145 days were put into a quart jar fitted with a copper screen cap. The jar was placed under running tap water in a laboratory sink for 3 days. After that, the water was run long enough every 2-3 days to effect a change of water on the seed. The seed remained in the water for 43 days.

Germination was also attempted on agar plates. Seed were soaked in tap water for 2-3 days and the viscous covering of each was removed to expose the endosperm. The seed were then treated for 2 min with 6% NaClO followed by a 5-min sterile distilled water rinse. Seed were sown individually on dwarf mistletoe infusion agar plates (50 g of dwarf mistletoe plants were chopped in an electric blender, steeped in distilled water (ca. 10 min), and 20 g of agar were added per 1,000 ml filtrate). Twenty-one seed of *A. campylopodium* that had been in dry, cold, laboratory storage for ca. 105 days and 11 seed of *A. tsugense* (Rosendahl) G. N. Jones that were collected from host twigs were so treated. The plates were stored in the dark at 10°C.

A "rag-doll" germinator was employed in one test. Four paper towels were moistened with distilled water and folded lengthwise to a width of 2 inches. The ends were folded over, the folded towels wrapped with heavy wax paper, and fastened with paper clips prior to being sterilized in an autoclave. Two hundred seed each of *A. laricis* and *A. campylopodium* were taken from dry, cold, storage, placed on the sterilized paper towels inside the "rag-doll," and tested for germination at each of three temperatures. One hundred seed of each species of dwarf mistletoe received further pretreatment for 5 min in 95% ethyl alcohol followed by 15 min in sterile distilled water. The second 100 seed of each species (controls) received no further treatment. The four lots were placed in separate sterilized "rag-dolls." Tests were run at 5°, 10°, and 15°C for 40 days.

Results

All seed tested for germination in the wet and dry germinators failed to germinate, regardless of pretreatment, temperature, moisture, or light conditions used. All seed pretreated with water only and tested in wet germinators molded; seed in dry germinators shriveled, but showed only slight amounts of mold development. Additional pretreatments with alcohol, sodium hypochlorite, hydrochloric acid, and sulfuric acid reduced the amount of mold development, but did not prevent it.

No molds developed on seed treated with pectinase or hemicellulase, which decomposed the external mucilaginous material of the seed. The 72-h pretreatment apparently was too long at the concentrations used; all seed so treated turned white and failed to germinate. Seed were not tested by the TTC or H₂O₂ method at the end of the germination period (91 days). Seed treated with the two enzymes for 36 h also failed to germinate in the dry germinators, but did not turn white. Decomposition of the mucilaginous material appeared to be less than in the 72-h treatment. Seed of *A. laricis* treated for 36 h subsequently were tested by the H₂O₂ method after 85 days in the dry germinators at 10°C. Percentage germination for pectinase treated seed was 22; for the hemicellulase treated seed, 16.

The horse-dung infusion and Douglas-fir bark extract failed to stimulate seed germination after 111 days in the germinators. Seed in the wet germinators molded and those in dry germinators shriveled. Posttreatment with H₂O₂ was not attempted because the treatment had not yet been developed.

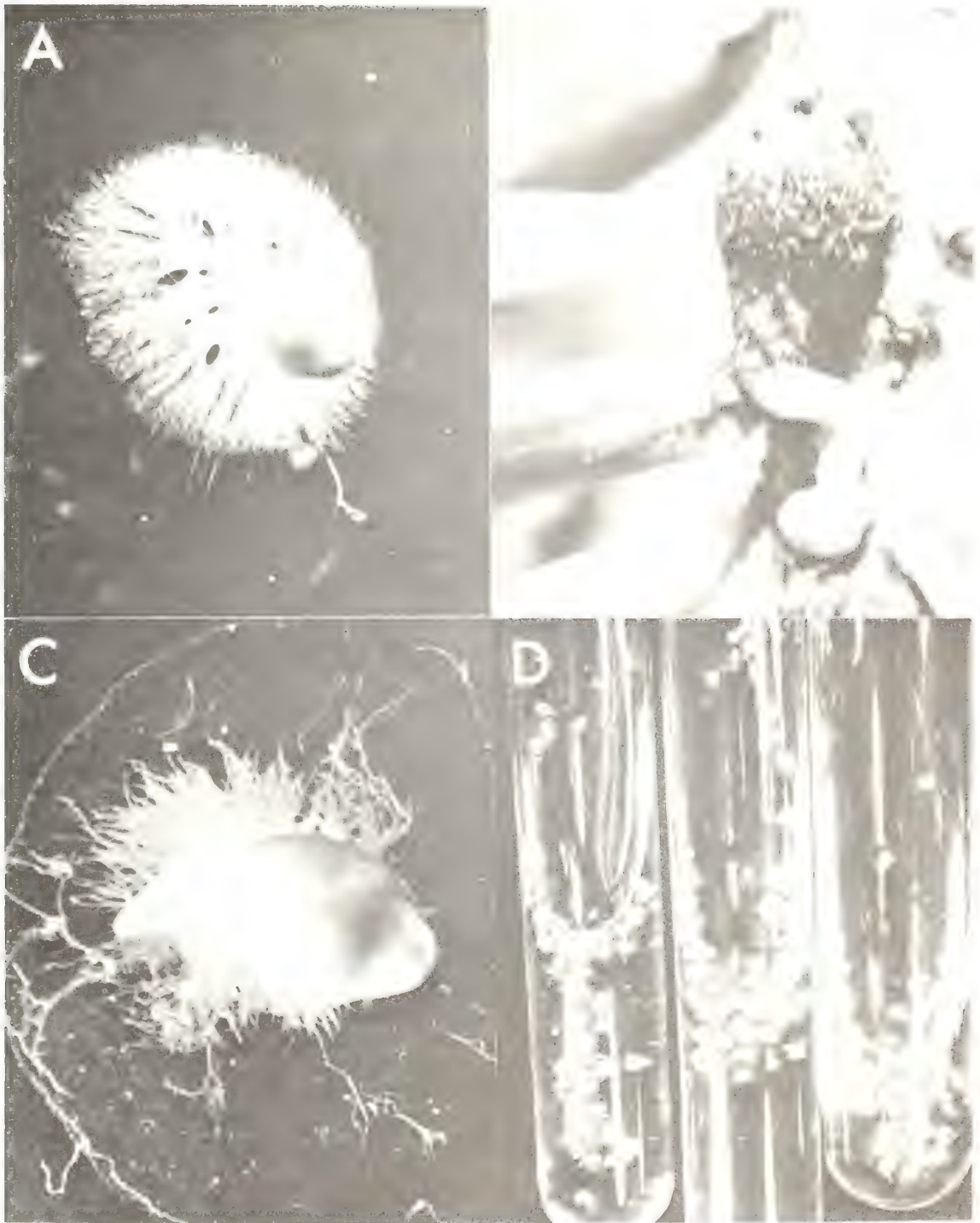


Figure 1.--(A) Seed with mucilage expanded. Seed was wetted with water to allow the mucilage to fully expand. Upon drying, the mucilage cemented the seed to the glass surface. X14.4. (B) Seed germinating in a solution. An irregular mound of tissue (holdfast) is attached to the bark. The radicle and is attached to the bark. (C) Seed germinated in 3% H_2O_2 solution and placed on a glass surface. Mucilage cells have been destroyed to the point where the seed is on the glass surface. X20. (D) Seed germinating in H_2O_2 solution.

The DMSO-treated seed showed no germination after 81 days, at which time a malfunction in the growth chamber controls resulted in temperatures exceeding 200°F, thus terminating the experiment. No molds developed on these seed.

After 88 days in the dry petri plate germinators, ethylene chlorohydrin-treated seed and the control had failed to germinate. The seed were placed at this time in H₂O₂ and the germinative capacity of all treated seed was zero, but the germinative capacity of the control sample (18-24 h water pretreatment only) was 60%. Although some seed in the control were molded, treated samples showed no mold development.

The germination tests employing hydrogen peroxide were very encouraging (Wicker 1962). Germination of laboratory stored seed was obvious after 4 days (fig. 1). Treatment was continued for 10 days with hope that all viable seed would germinate. Results of the initial test with *A. laricis* seed, conducted at room temperature under dark conditions, are given in table 2.

Hydrogen peroxide (3%) was equally effective for determining the germinative capacities of dwarf mistletoe seed for the eight taxa tested (table 3). The stimulatory effect of H₂O₂ was enhanced by pretreating the seed with distilled water for 18-24 h (table 4).

Comparisons of the H₂O₂ (3%) germination test with the 0.1% aqueous TTC viability test showed that percentage germination in H₂O₂ was always less than viability as indicated by the TTC test for the three taxa tested. The data (table 5) represent averages for the three samples of 50 seed each.

The dwarf mistletoe seed treated with 0.1% aqueous TTC for 3 days and subsequently treated for 10 days with 3% H₂O₂ failed to germinate. The controls, however, showed 74% germination for *A. campylopodium* and 66% for *A. laricis*.

None of the dwarf mistletoe seed treated with thiamine, chloride, glutathione, or raw coconut milk germinated. Upon termination of these tests, seed were treated with 3% H₂O₂. Germination was uniformly low, ranging from 12% to 22% (table 6).

Seed of *A. laricis*, which were continuously submerged in water, showed a germination percentage of 27. The nongerminating seed were not tested for viability (TTC) nor treated with H₂O₂.

Molds were again a major problem in germination tests using agar plates. Only three *A. campylopodium* seed and one *A. tsugense* seed germinated. The rest were destroyed by molds. All the seeded plates were placed in the incubator in an inverted position to reduce the chance of contamination from external sources. The four seed that germinated showed a tropic response; radicles grew down away from the agar surface.

Fungi that developed on agar plates seeded with *A. campylopodium* were predominantly *Penicillium* spp. and *Aspergillus* spp., whereas the only fungus found on plates seeded with *A. tsugense* was *Pestalotia maculiformans* Guba & Zeller.

All seed tested in "rag-doll" germinators failed to germinate. The controls (water pretreatments) were severely molded with *Penicillium* spp. Alcohol-treated seed had molded also, but not as much as the controls. The alcohol pretreatment was later found to be toxic to seed. Seed so treated and then placed in dry germinators for 150 days at 0°, 5°, and 10°C did not germinate. But, when seed were subsequently treated with H₂O₂, with appropriate checks, the alcohol pretreatment reduced germination by 16%-60%.

Table 2.--Percentage germination (50 seed/sam.) of
Arceuthobium laricis treated with H_2O_2

H_2O_2 (%)	Germination	Average number of radicle
0.0 (water)	0 (84) ²	
1.0	84	0.35
2.0	78	.49
3.0	76	.4
4.0	82	.54
5.0	76	.60
Dry	0 (82)	

¹Seed had been stored 150 days, 5°C, 35-45% RH, dark. Pretreated 18-24 h with sterile distilled water following removal from storage and prior to H_2O_2 treatment.

²Subsequent treatment for 10 days with 3% H_2O_2 gave this percentage germination.

Table 3.--Germination of 100-seed samples¹ treated with 3% H_2O_2 at room temperature for 10 days

Dwarf mistletoe (<i>Arceuthobium</i>)	Germination
<i>A. abietinum</i>	77
<i>A. americanum</i>	78
<i>A. campylopodium</i>	85
<i>A. cyanocarpum</i> Coulter and Nelson ²	57
<i>A. douglasii</i>	56
<i>A. laricis</i>	84
<i>A. pusillum</i> Peck ³	48
<i>A. tsugense</i>	68

¹Seed had been stored 30-165 days, 5°C, 35-45% RH, dark. Pretreated 18-24 h with sterile distilled water prior to H_2O_2 treatment.

²205 seed.

³257 seed.

Table 4.--Effect of pretreatment in distilled water on seed germination of 100-seed samples¹ treated with 3% H_2O_2 at room temperature for 10 days

Dwarf mistletoe (<i>Arceuthobium</i>)	Water pretreatment	Germination	Average number of radicle
<i>A. americanum</i>	Yes	78	0.59
<i>A. americanum</i>	No	68	.52
<i>A. laricis</i>	Yes	76	.51
<i>A. laricis</i>	No	70	.26

¹Seed had been stored 160 days, 5°C, 35-45% RH, dark.

Table 5.--Comparison of H_2O_2 germination and TTC viability tests

Dwarf mistletoe (<i>Arceuthobium</i>)	:	Viability (0.1% aqueous TTC)	:	Germination (3% H_2O_2 ; 22°C)
	:	%	:	%
<i>A. americanum</i>		84		77
<i>A. campylopodum</i>		90		78
<i>A. laricis</i>		79		71

Table 6.--Germination of seed placed in H_2O_2 after being treated with growth substances

Treatment	:	Dwarf mistletoe (<i>Arceuthobium</i>)	:	Germination ¹
	:		:	%
Thiamine chloride		<i>A. campylopodium</i>		21
		<i>A. laricis</i>		17
Glutathione		<i>A. campylopodium</i>		13
		<i>A. laricis</i>		18
Coconut milk		<i>A. campylopodium</i>		12
		<i>A. laricis</i>		22

¹3% H_2O_2 solution, room temperature, 10 days.

SEED DORMANCY

Materials and Methods

Several hundred seed of *A. americanum* Nuttall ex Engelm., *A. campylopodum*, *A. laricis*, and *A. douglasii* Engelm. were collected during a 2-day period in mid-September 1962. At the time of collection, sample lots of 100 seed of each taxon were soaked in water for 12-15 h, then placed in small vials containing 20 ml of 3% H_2O_2 solution, and sealed. In the interim, the remaining seed were held in dry, cold, laboratory storage. Each week thereafter, lots of 100 seed were removed from storage and placed in H_2O_2 until maximum germination was attained. Each weekly series of tests was of 10 days duration at room temperature in diurnal light.

Results

This experiment was terminated after 5 weeks. Maximum germination apparently was reached prior to its termination (fig. 2). The seed of *A. laricis* were of poor quality as is verified later, but the delay in germination is demonstrable.

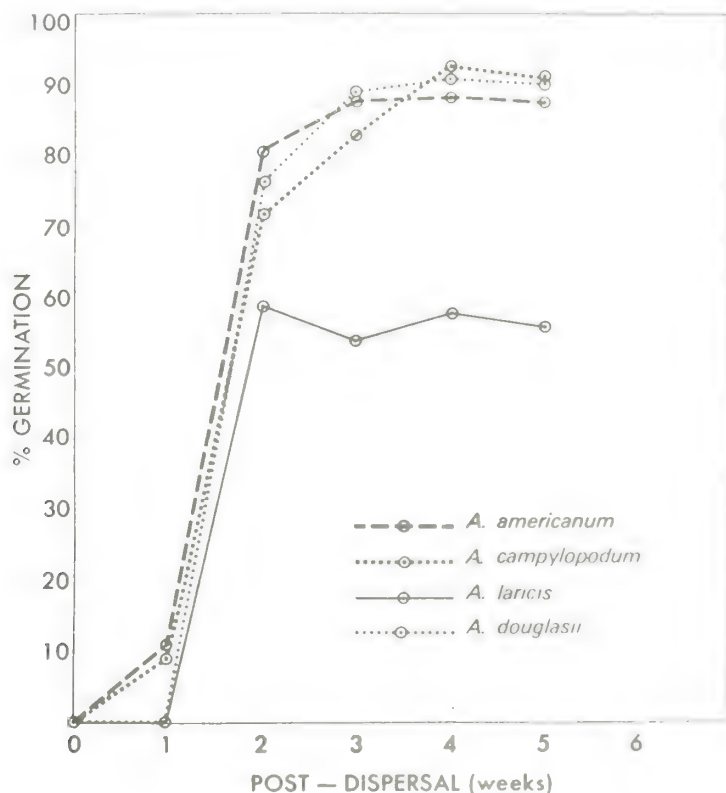


Figure 2.--Percentage germination of dwarf mistletoe (*Arceuthobium*) seed during the first 5 weeks of storage following dissemination.

TEMPERATURE

Materials and Methods

All seed used to study temperature effects had been in dry, cold, laboratory storage.

Eight hundred *A. laricis* seed were removed from storage after 60 days and counted into lots of 50 seed each. Germinative capacity (3% H_2O_2) was 84%. Duplicate lots were tested at each temperature employed. One seed lot received a 24-h pretreatment in sterile distilled water. The second lot received a 24-h soak in tap water, 15 min in 95% ethyl alcohol, and a 15-min rinse in sterile distilled water. Seed lots were scattered in open petri plates and stored in incubators at 0°, 5°, 10°, 15°, 20°, and 25°C. Identical samples were frozen at -3°C, for 32 days and then placed at 10°C for 145 days.

There was little to no control of the relative humidity in these incubators because they were being used by other workers. The incubators were kept dark, except when the doors were open. Germination tests (3% H_2O_2) were run on all seed samples after 177 days.

In another experiment, seed of three dwarf mistletoes that had been in dry, cold, laboratory storage for 30 days were counted into lots of 50 seed each, scattered in open, sterilized petri plates, and placed in dark incubators set at desired temperatures. Seed received no pretreatment. Sample lots were tested for germinability (3% H_2O_2) after 1, 3, 6, 9, and 12 mo. Germinative capacity was 95% for *A. campylopodum*, 89% for *A. douglasii*, and 53% for *A. laricis* when removed from storage.

Results

Data (table 7) show that storage temperatures affect seed viability and indicate the rather pronounced detrimental effects of the ethyl alcohol pretreatment on *A. laricis* seed. Additional data on the time-temperature-viability relationships for seed of three species of *Arceuthobium* during storage are shown in figures 3, 4, and 5. In all three species, optimum storage temperature is near 0°C. Seed source was a confounding factor in these tests. *Arceuthobium campylopodum* seed were from a single source. *Arceuthobium douglasii* and *A. laricis* seed were from mixed sources and, hence, may not have been uniform.

Table 7.--Effect of storage temperatures on viability of seed of *Arceuthobium laricis*

Temperature (°C)	Water	Ethyl alcohol, 95%	Water	Germination (5% H ₂ O)
	<i>h</i> ₁	<i>h</i> ₂	<i>h</i> ₃	
-3 ²	24	17	15	28
-3 ²	24		0	12
0	24		15	12
0	24	0	0	74
5	24	15	15	14
5	24	0	0	60
10	24	15	15	12
10	24	0	0	52
15	24	15	15	0
15	24	0	0	0
20	24	15	15	0
20	24	0	0	0
25	24	15	15	0
25	24	0	0	0

¹Based on 50 seed/sample after 177 days' storage.

²32 days at -3°C; 145 days at 10°C.

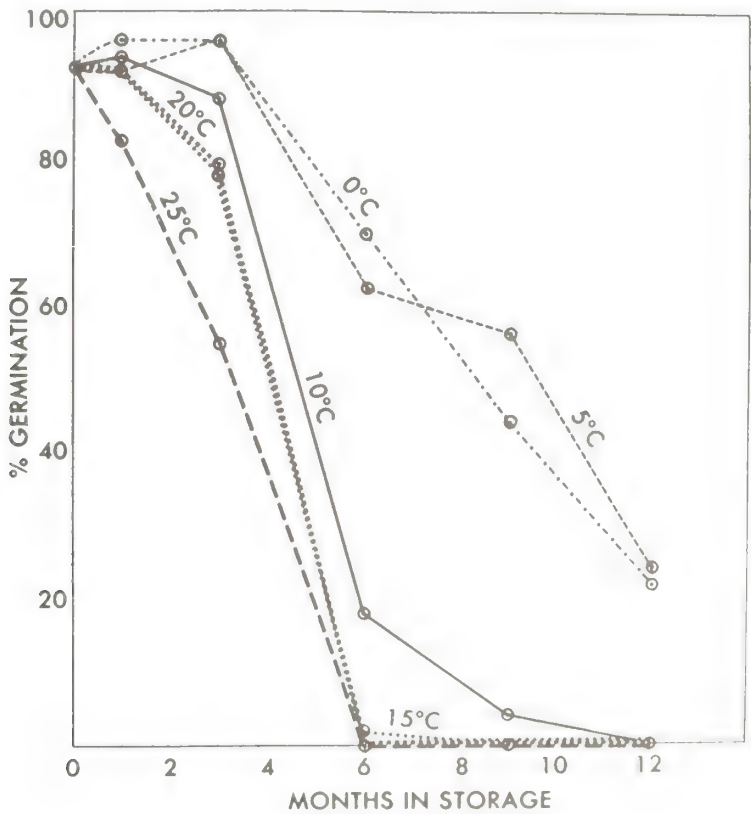


Figure 3.--Effect of storage temperatures on germinability of seed of *Arceuthobium campylopodum*.

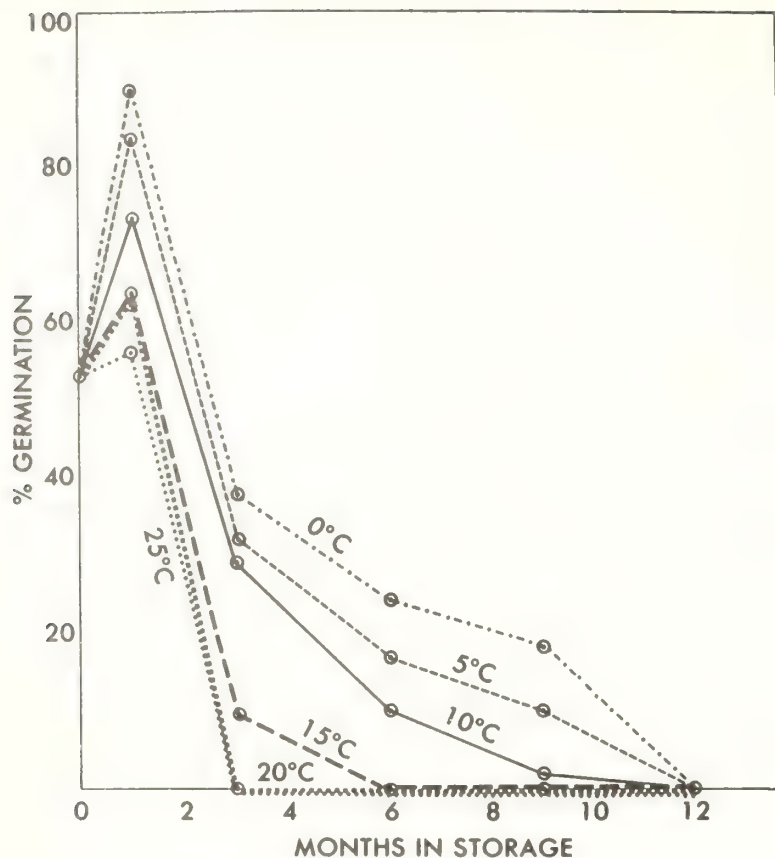


Figure 4.--Effect of storage temperatures on germinability of seed of *Arceuthobium laricis*.

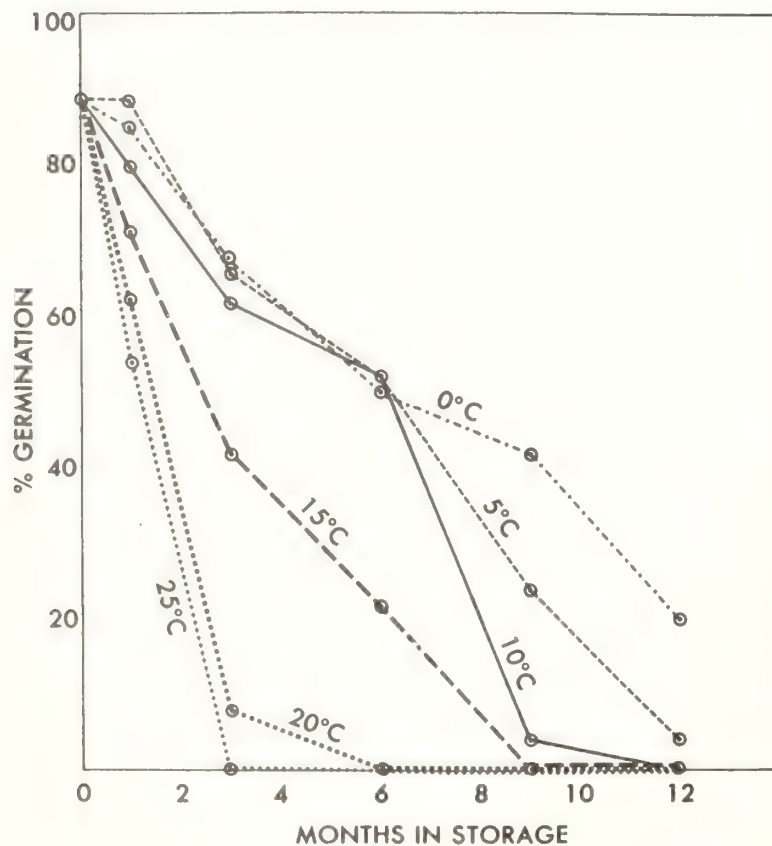


Figure 5.--Effect of storage temperatures on germinability of seed of *Arceuthobium douglasii*.

RELATIVE HUMIDITY

Materials and Methods

Seed of *A. campylopodium* and *A. lariciis* were removed from dry, cold, laboratory storage (ca. 120 days), soaked in tap water for 12-14 h, and counted into lots of 50 seed each. Each lot was placed on a 4-in square of cheesecloth. Corners of the cheesecloth were brought together and fastened with wire, thus enclosing the seed in a cloth sack. Seed were soaked for 15 min in a 0.1% mercuric chloride solution, washed for 5 min in each of three successive changes of sterile distilled water (Scharpf and Parmeter 1962), removed from the cheesecloth, and scattered in sterile glass vials (7x2 cm). The vials were then placed in 1-qt widemouthed jars containing saturated salt solutions, prepared according to the method described by Winston and Bates (1960). Three lots of 50 seed each were placed into each container, which was then sealed. Four different relative humidities were tested at each of two temperatures (5° and 20°C). Seed samples were removed after 30, 60, and 90 days. Percentage germination was determined by the hydrogen peroxide method (3%, 10 days, room light).

Results

At the beginning of the test (i.e., after 120 days dry, cold, laboratory storage), germination was 86% for *A. campylopodium* seed and 55% for *A. lariciis* seed. The germinative capacity of *A. lariciis* seed was too low to indicate the effects of relative humidity or of temperature. The effect of temperature on *A. campylopodium* was pronounced (table 8). The data further suggest that high relative humidities may adversely affect the viability of stored seed.

Table 8.--Germination of dwarf mistletoe (*Arceuthobium*) seed after 30-90 days storage at 5° and 20°C at four different relative humidities

Dwarf mistletoe	Temperature	Relative humidity	Germination ¹		
			30 days	60 days	90 days
	°C	%	%	%	%
<i>A. campylopodum</i>	5	14.0	74	80	70
	5	40.0	72	78	68
	5	75.0	64	68	34
	5	98.5	66	66	52
	20	12.5	8	14	0
	20	38.0	10	8	0
	20	75.0	4	10	0
	20	98.0	20	20	20
<i>A. laricis</i>	5	14.0	2	4	0
	5	40.0	10	6	0
	5	75.0	2	6	0
	5	98.5	8	4	0
	20	12.5	2	0	0
	20	38.0	0	0	0
	20	75.0	2	0	0
	20	98.0	0	0	0

¹Germination after 10 days in 3% H₂O₂, 22-23°C.

²Contaminated by *Penicillium* spp.

LIGHT

Materials and Methods

Seed of *A. campylopodium* that had been in dry, cold, laboratory storage for ca. 65 days were counted into lots of 100 seed each and scattered in open petri plates. Seed were then stored at 5°C, 35-45% RH, and ca. 700 fc of light from white fluorescent bulbs for 8 h each day for 6 mo. Samples were tested for viability at 60-day intervals by the TTC method. Seed lots left in dry, cold, laboratory storage (dark) were used as checks.

In a second experiment, light intensity was increased to ca. 3,000 fc for 8 h each day. Seed of *A. campylopodium* and *A. laricis* that had been in dry, cold, laboratory storage for 30 days were soaked in tap water for 18-24 h, then counted into lots of 100 seed each and scattered in open petri plates. Temperature and relative humidity were the same as before. Duplicate samples (controls) were stored in the dark. Samples were tested for germinative capacity every 30 days by the hydrogen peroxide method.

Results

Based on two 100-seed samples and determined by the aqueous TTC method, viability of *A. campylopodium* seed was 90.5% at the beginning of the first light treatment. Light had no effect on seed viability under the conditions of the experiment (table 9).

Table 9.--Viability of *Arceuthobium campylopodium* seed stored under illumination and in the dark

Treatment time (days)	Viability ¹	
	Light	Dark
	or %	
60	84	81
120	68	71
180	54	56

¹Determined by 0.1% TTC (in water).

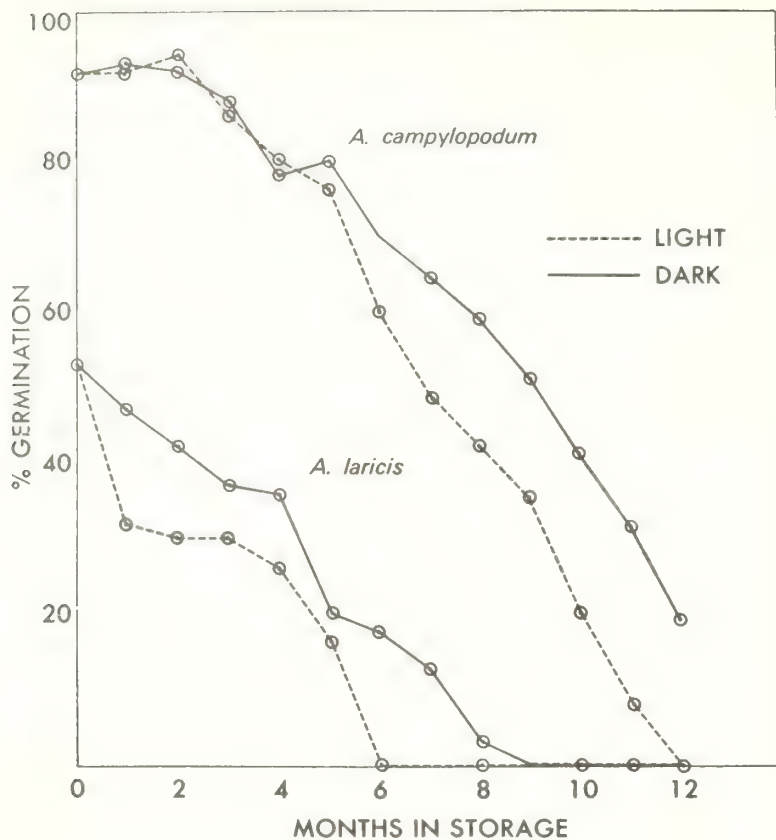


Figure 6.--Effect of ca. 3,000 foot-candles of light (8 hours/day) during storage (5°C, 35-45% RH) on the germinability of dwarf mistletoe seed.

Results of the second experiment are illustrated in figure 6. The seed of *A. campylopodum* were all from the same source and were of high quality (93% viability) at the beginning of the tests. Differences between storage under illumination and dark were not marked until after 6 mo of treatment. This suggests that the effect at this lighting (3,000 fc, 8 h/day) was one of temperature rather than light.

All *A. laricis* seed were also from a single source but the viability of these seed was relatively low (53%) at the start of the tests. Differences between light and dark were rather sharp after 30 days of treatment.

MOLDS AND BACTERIA

Materials and Methods

Fungi and bacteria from molded seed were grown on 2.5% potato dextrose (PDA) plates. Each plate was inoculated with a single, molded seed and incubated in the dark at 20°C for a week. Successive transfers of all colonies were made until pure cultures were obtained. Seed used were from three sources: (1) *A. laricis* collected at Priest River Experimental Forest (PREF), Priest River, Idaho, that molded during stratification in moist, sterile sand (Wicker 1965, 1967a); (2) 20 seed each of (a) *A. laricis* collected at Quartz Creek and PREF, Bonner County, Idaho; (b) *A. laricis* from Sherman Creek, Ferry County, Wash.; and (c) *A. campylopodum* collected 4 miles north of Spangle, Spokane County, Wash., that had molded during moist laboratory storage at 5°C (Wicker 1965, 1967a); and (3) thirty-eight seed of *A. laricis* collected at PREF and 42 seeds of *A. douglasii* collected 3 miles east of Viola, Latah County, Idaho, that molded during the winter in the field on their coniferous hosts at an artificial inoculation plot, PREF.

Results

The fungal isolates from seeds of Source 1 were tentatively identified to species. Fungi isolated from 78 seeded PDA plates and their frequency of occurrence were as follows: *Alternaria tenuis* Nees, 79.5%; *Mucor sphaerosporus* Hagem, 70.5%; *Lignorum* (Tode) Hatz, 60.3%; *Rhizopus microsporus* van Tiegh. and *Rhizopus* (Ehr. ex Fr.) Vuill., 53.8%; *Aspergillus* spp., 29.5%; *Fusarium* spp., 20.5%; miscellaneous fungi, 6.4%.

Many fungi were isolated from seeds of Source 2 (table 10). None of them have been identified to species. Some isolates could not be identified even at the generic level; these are shown in table 10 as "miscellaneous fungi." Source 1 *A. laricis* and *A. douglasii* produced even a greater array of fungi (table 11). Some rarely occurring, nonsporulating isolates were not identified and are shown as "miscellaneous fungi" in the table.

Table 10.--Fungi isolated from dwarf mistletoe (*Arceuthobium*) seed which molded during moist, cold storage

Genera	Frequency	
	<i>A. campylopodum</i>	<i>A. laricis</i>
	%	%
<i>Cephalosporium</i>	--	55.0
<i>Alternaria</i>	55.0	45.0
<i>Aureobasidium</i>	35.0	40.0
<i>Candida</i>	40.0	10.0
<i>Paecilomyces</i>	40.0	20.0
<i>Penicillium</i>	--	35.0
<i>Hormiscium</i>	--	25.0
<i>Kloeckera</i>	--	25.0
<i>Stemphylium</i>	25.0	--
<i>Streptomyces</i>	20.0	--
<i>Trichoderma</i>	15.0	15.0
<i>Botrytis</i>	--	15.0
<i>Pestalotia</i>	10.0	--
<i>Rhizoctonia</i>	--	5.0
<i>Cladosporium</i>	--	5.0
Miscellaneous fungi	15.0	35.0

Table 11.--Fungi isolated from dwarf mistletoe (*Arceuthobium*) seed which molded on the host trees in the field

Genera	Frequency	
	<i>A. laricis</i>	<i>A. douglasii</i>
	%	%
<i>Epicoccum</i>	73.7	52.4
<i>Stemphylium</i>	13.2	23.8
<i>Hormiscium</i>	7.9	21.4
<i>Phyllosticta</i>	13.2	9.5
<i>Coniothyrium</i>	--	11.9
<i>Aureobasidium</i>	7.9	9.5
<i>Alternaria</i>	7.9	7.1
<i>Candida</i>	7.9	4.8
<i>Rhizoctonia</i>	5.3	7.1
<i>Streptomyces</i>	5.3	--
<i>Fusarium</i>	5.3	--
<i>Monilia</i>	2.6	--
<i>Pestalotia</i>	2.6	--
<i>Mucor</i>	2.6	--
<i>Cephalosporium</i>	2.6	--
<i>Helminthosporium</i>	2.6	--
<i>Penicillium</i>	--	2.4
<i>Paecilomyces</i>	--	2.4
Miscellaneous fungi	18.4	31.0
Yeast	15.8	2.4
Bacteria	23.7	16.7

DISCUSSION

Various physical, biochemical, and cultural factors, as well as direct germination, have been employed to measure seed quality (viability and germinability). In some of the literature (U.S. Dep. Agric. 1948; Ching and Parker 1958; Kramer and Kozlowski 1960; Mayer and Poljakoff-Mayber 1963), viability and germinability are not clearly differentiated. In reporting these investigations, the two terms are used as defined by Amen (1963) and Webster's Third International Dictionary. Viability--the ability to maintain life--may or may not be a measure of germinability. The fact that a seed is living does not imply that it will germinate. Rarely is germinability 100% of viability. Viability tends to decrease with time; nevertheless, the germinability of those seed that are still viable may increase with age (Amen 1963). Germinability--the ability of an embryo to resume growth--is a measure of viability, but the reverse is not necessarily true.

Viability of dwarf mistletoe seed (table 1) is readily and rather accurately determined by the 0.1% aqueous 2,3,5-triphenyl tetrazolium chloride (TTC) viability test. The test is run at room temperature (22°C) for 3 days in the dark. The ethanol TTC test was unsatisfactory for *Arceuthobium* seed under the conditions of the experiments. The ethanol insolubility of the viscin, which coats the seed, perhaps was a limiting factor in these tests. Also, 95% ethanol is toxic to seed (table 7), probably because it rapidly reaches the embryo in the area not covered by the viscin. Viability determined by the aqueous TTC test was 7-12% higher than germinability determined by the H₂O₂ method (table 5).

The most important environmental requirements for seed germination are water, oxygen, and favorable temperature. Light is required by some seed, but is not essential for germination of *Arceuthobium* spp. Specific requirements vary with plant species. The important processes required for seed germination are water absorption, digestion, respiration, and assimilation (Kramer and Kozlowski 1960; Mayer and Poljakoff-Mayber 1963). According to Toole and Hendricks (1956), seed germination reflects a balance between germination promoters and inhibitors; the ratio is specific for each species.

All conditions defined for seed germination were met individually or in combinations by these investigations. However, mature, naturally discharged dwarf mistletoe seed failed to germinate during laboratory storage. Most factors tested, e.g., stimulants, sterilants, enzymes, temperature, relative humidities, light, etc., failed to stimulate germination.

Stored seed placed on agar plates germinated if they remained free of mold fungi. This is a laborious and impractical method when working with large numbers of seed. Some seed germinated when submerged in water for 43 days. Preparation time and the low percentage germination restrict the usefulness of this method. Nongerminating seed were not subsequently treated with H_2O_2 ; but, it is doubtful that the short storage in water is detrimental because some seed germinated. Both of these methods require 35-50 days for germination of stored seed; however, results suggest that free water is necessary for germination. Bonga (1972) has recently reported evidence which also supports this conclusion. The low germinative capacity of dwarf mistletoe seed submerged in water suggests that oxygen was a limiting factor. Later investigations showed that temperature was also a limiting factor.

Hydrogen peroxide stimulates germination of stored dwarf mistletoe seed; germination is visible macroscopically within 4 days. This treatment has proved to be an invaluable tool in investigations of seed storage conditions, dormancy, and ecology and in artificial inoculation studies. Problems created by molds and bacteria are eliminated. Tests with H_2O_2 have been run under light and dark conditions and at 10°C and 22°C without significant variation. Germination is so rapid in H_2O_2 that the effects of temperature are nullified. Thus, asepsis, rapidity, and simplicity are major attributes of the H_2O_2 method. Rate of germination, as measured by radicle length, increased as concentrations of the test solution increased up to 5% H_2O_2 solution.

The H_2O_2 germination method was effective for seed of the eight taxa tested, including *A. pusillum*. Bonga (1965) cited my report (Wicker 1962) that H_2O_2 stimulated seed germination in several dwarf mistletoes, but concluded from his own data that "such a reduction in germination time,...was not noted for *A. pusillum*." He might have corroborated my findings if he had followed the germination testing method that I reported. The stimulatory effect is enhanced by pretreating the seed for 18-24 h in distilled water. Percentage viability was lower when determined by this method than by the TTC method. However, the H_2O_2 method is a germinability test as well as a viability test. It is more reliable and more useful than chemical staining tests for viability because such tests check on only one definite reaction which may be correlated with germinability. Furthermore, seed treated with TTC for 3 days and subsequently placed in H_2O_2 for 10 days did not germinate. Thus, although TTC is useful for a destructive viability test, it is lethal to seed of *Arceuthobium* spp. The TTC staining test results in formation of color-visible products in the presence of active oxidizing enzymes and may inactivate the enzymes.

The mode of stimulation by H_2O_2 in germination is not known. Ching (1959) discussed four possible stimulatory mechanisms of H_2O_2 . The H_2O_2 treatment supplies seed with both water and oxygen but since H_2O does not show the stimulating effect of H_2O_2 , the additional oxygen must be the key factor. Based on this assumption, the first approach to an understanding of the mode of activating germination would be to determine the fate of the oxygen. Perhaps radioactive tracer techniques employing $H_2O_2^{14}$ or $H_2O_2^{15}$ could be applied here.

Data illustrated in figure 2 indicate that a short period of seed dormancy may exist for the four taxa investigated. The concept of seed dormancy was recently reviewed by Amen (1963). He lists five major causes of seed dormancy: (1) rudimentary embryos; (2) physiologically immature embryos (inactive enzyme systems); (3) mechanically resistant seed coats; (4) impermeable seed coats; and (5) presence of germination

inhibitors. In general, seed dormancy is classified as either seed coat or embryo dormancy. The duration of seed dormancy ranges widely among species from a few days to several years. Seed dormancy is specific for the species, but not all seed of a given species are necessarily dormant.

Arceuthobium does not have a true seed coat (Johnson 1888; Thoday and Johnson 1935; Gill 1935; Cohen 1962, 1963). The seed consists essentially of a naked embryo and endosperm encased by the crushed tissues of the ovarian mound or the pericarp of the fruit, or perhaps both (Gill and Hawksworth 1961). Therefore, seed coat dormancy cannot be a factor.

Scharpf and Parmeter (1962) state that *A. campylopodum* seed require no after-ripening period. However, I believe their data on seed germination clearly indicate an after-ripening period because some seed germinated within 30 days but maximum germination was not achieved until after 60-90 days. Furthermore, if the enzymatic and chemical changes necessary for germination occur in less than 30 days, this period of embryo dormancy could not be defined in their data because 30 was the minimum days of germination used. Beckman and Roth (1968) speak of "a dormancy factor of unknown nature....The presumed inhibitor, probably of a chemical nature and associated with the seed covering,...." Cohen (1963) reported that the embryo of dwarf mistletoe seed develops directly into the seedling without cessation of growth, a condition which he calls "vivipary." Hawksworth (1961) stated that seed of *A. vaginatum* subsp. *virgatum* (Engelm.) Hawksworth and Wiens germinate within 1 month following dissemination in late July and early August.

If dwarf mistletoe seed can be assumed to be mature at the time of natural dissemination, then the data (fig. 2) would indicate a dormant period of ca. 24 days for the four species tested. The validity of the assumption is questionable, however, because physiological maturity at the time of seed dissemination is not completely understood.

Temperature and relative humidity are the critical factors in respect to viability and longevity during seed storage. Higher temperatures most likely increase cell metabolism and enzyme activity. High relative humidities or free water at low temperatures not only provide conditions favorable for development of molds but probably cause deficient oxygen supply. High moisture content lowers seed tolerance to heat (Stanley and Butler 1961).

The effect of relative humidity is not as striking as that of temperature (table 8). Nevertheless, both trends are there for seed of *A. campylopodum*. Data on *A. laricis* are not reliable because seed were of poor quality (35% viability). The effects of both increasing temperature and relative humidity (>75%) decreased germination.

Temperature affects both viability and longevity of stored seed. A valid comparison cannot be made with the data in table 8 between *A. campylopodum* and *A. laricis*, because viability was not comparable at the beginning of the experiment. The data on *A. laricis* (table 7) indicate the temperature effect. The alcohol pretreatment markedly reduces germination as does storage at constant freezing temperatures (-3°C). The maximum temperature for storage of *A. campylopodum* (fig. 3), *A. laricis* (fig. 4), and *A. douglasii* (fig. 5) seed for 10 months or more is between 5° and 10°C. Under the conditions of the experiment, the optimum temperature for all three taxa is the lowest temperature used, 0°C. These storage temperatures are in agreement with those reported by Scharpf and Parmeter (1962) for *A. campylopodum*.

An effect of light on seed viability was not detected under the conditions of these experiments. Light did not affect viability of *A. campylopodum* seed after 180 days of storage (table 9). Results presented in figure 6 are considered to be due to temperature rather than light *per se*.

Molds were a very disturbing problem throughout the investigations of seed storage, viability, and germination. The only reference to molds in the published literature on dwarf mistletoes was by Scharpf and Parmeter (1962), although J. R. Weir mentions the problem in unpublished field notes. Apparently, Beckman and Roth (1968) encountered this problem, but not Knutson (1971). Most of the literature on molds of seed deal with stored grains and forest tree seed (Christensen 1957; Gibson 1957; Lawrence and Rediske 1962; Salisbury 1953; Shea 1960; Timonin 1964; Noble and others 1958; Tuite and Christensen 1955, 1957).

The fungi listed do not represent the range of seed coat microflora for dwarf mistletoes because conditions of experimentation (media, temperature, pH, light, etc.) were selective in respect to the growth of fungi; therefore, the tables present a restricted sample of the seed microflora for a particular set of conditions. The fungi (tables 10-11) isolated also reflect the different localities of seed collection. *Arceuthobium campylopodum* came from a single location near Spangle, Wash., whereas *A. laricis* came from Sherman Creek, Ferry County, Wash., and Priest River Experimental Forest in northern Idaho. *Arceuthobium laricis* seed (table 11) were collected at Priest River Experimental Forest and *A. douglasii* at Sherman Creek, Ferry County, Wash., and 3 miles east of Viola, Latah County, Idaho. The majority of the fungi are common airborne contaminants, but their effect on seed viability and decay, particularly under conditions of high relative humidity, certainly deserve recognition. The mucilaginous coating of dwarf mistletoe seed, when moist, is a suitable substrate for these fungi. Seed may be destroyed by these fungi in the field during the overwintering period as well as during laboratory storage (Wicker 1967b). In this respect, they can be considered a facet of biological control.

CONCLUSIONS

Viability of dwarf mistletoe seed is accurately measured by the aqueous TTC test. Hydrogen peroxide rapidly stimulates germination. There is a brief period (ca. 24 days) of physiological dormancy indicated for the four taxa tested.

Temperature and relative humidity affect vitality and longevity of dwarf mistletoe seed. An effect of light was not detected. Free moisture for prolonged periods is conducive to mold development and deficient oxygen for metabolic processes. The mucilage covering the seed is a suitable substrate, when moist, for numerous fungi which may destroy the seed. I concur with Kuijt (1960) in that "no particularly unusual conditions" are required for germination.

It is established that many factors of the environment affect vitality, longevity, and germinability of dwarf mistletoe seed. It is well to remember that these factors never function individually or constantly in their effect upon the organism. Therefore, the effects of environmental factors upon the vital processes of dwarf mistletoe seed are meaningful only in terms of their composite actions and interactions.

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Information on seed viability, germinability, dormancy, and longevity for several species of Arceuthobium is presented and methods for testing these qualities during storage are described. Data on the effects of temperature, relative humidity, and light on seed vitality are reported. Some mold fungi capable of reducing the vitality of dwarf mistletoe seed are identified.

KEYWORDS: hydrogen peroxide, 2,3,5-triphenyl-tetrazolium chloride, Arceuthobium abietinum, Arceuthobium americanum, Arceuthobium campylopodum, Arceuthobium douglasii, Arceuthobium laricinis, Arceuthobium tsugense, Arceuthobium cyanocarpum, Arceuthobium pusillum.

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**HELICOPTER LOGGING:
A MODEL FOR
LOCATING LANDINGS**

Louis T. Edging
and
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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Roger R. Bay, Director

THE AUTHORS

LOUIS T. EGGING is a Graduate Research Assistant, presently completing work for his master's degree at Montana State University, Bozeman, in Industrial and Management Engineering. He received his B. A. degree in Math from Carroll College, Helena, Montana, and his B. S. degree in Industrial and Management Engineering from M. S. U. For the past 3 years, he has been working with Intermountain Station in Bozeman on Logging Systems studies.

DAVID F. GIBSON is Associate Professor, Industrial and Management Engineering, Montana State University. For the past 2 years, he has been working cooperatively with the Intermountain Station's Forest Engineering Research Unit at Bozeman as a Research Industrial Engineer under the Intergovernmental Personnel Act. He holds B. S., M. S., and Ph. D. degrees in Industrial Engineering from Purdue University.

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ABSTRACT

Presented are a model and an accompanying computer program that optimally locate landing areas for a helicopter logging operation. Given a haul road, unit centroids, volumes of timber to be harvested, and helicopter operating parameters, landings are located so as to minimize yarding, hauling, and landing construction costs. The model considers constraints such as areas that are not suitable for landings and topographical obstacles. Written in FORTRAN IV, the computer program affords several evaluation and output options. Two examples are provided.

INTRODUCTION

In recent years, helicopter logging has emerged from experimental stages to become a viable alternative to conventional harvesting systems. Helicopter logging has a number of attractive advantages under certain conditions and management objectives. These include minimal environmental impact and the ability to harvest heretofore inaccessible timber. As a result, the volume of timber harvested by means of helicopter systems has been increasing steadily each year.

Binkley [1972] Edholm (1973, 1974), and Stevens (1972, 1973) have reported the general production and cost aspects of helicopter logging. The studies show that helicopter logging is expensive and warrants efforts to design an operating system in the most economical manner possible. Gibson (1974) developed a cost model that, given parameters of a system, specified optimum refueling of the aircraft.

This paper presents another tool for designing and managing a helicopter logging operation by presenting a computer model that specifies the number and location of landings to which the timber should be yarded. Considerations include areas not suitable for landings, and flight path restrictions such as ridges or other obstacles. Alternative landing sites are evaluated by total cost of yarding, landing construction, and hauling.

STATEMENT OF THE PROBLEM

Timber felled and "marked for turns" (logs identified to be grouped together as a load) is yarded to landings that are located on or in close proximity to a preexisting road. The timber is then loaded on trucks and hauled to the mill. Location and the number of landings affect (1) yarding costs, (2) landing construction costs, and (3) hauling costs. Topographical features often influence flight paths and landing selection. This paper is addressed to the problem of locating landings to minimize costs and yet satisfy constraints.

Locating helicopter landings is a special case of the generalized Weber problem, which is concerned with locating facilities within a given space so as to minimize a cost function. Many variations of the problem have been defined and include the consideration of various measures of distance (rectilinear, Euclidean, square of Euclidean), costs, and other features. Notable treatments of the problem include those by Kuhn and Kuenne (1962), Bellman (1965), Cooper (1963, 1968), Hakimi (1964), Levy (1967), and Cabot and others (1970).

The treatment presented in this paper is unique in several respects. First, although Euclidean distances are used to determine yarding costs, obstacles may be present: a flight path may be a series of linear line segments routed around a ridge or other obstacle, as opposed to a single path. Secondly, the costs of constructing landings has not only a fixed component, but also a variable one as well, which is dependent upon the amount of timber yarded to it. Also, a second transportation cost--the hauling cost--is included.

The extensive literature related to the generalized Weber problem will not be reviewed here. Nor will the computational techniques previously developed be enriched to extend the model to more general applications. This may be done in a subsequent paper. The purpose of this paper is to define the problem of designing and managing helicopter logging systems and to provide a FORTRAN IV program for locating landings.

A statement of the problem follows:

Given:

1. a haul road that can be represented by a set of linear line segments,
2. units to be logged, together with their respective centroids and timber volumes,
3. road segments infeasible for landing locations,
4. ridges or other topographical obstacles (which can be represented by linear line segments) that may preclude direct flight paths between units and landings, and
5. system costs and operating characteristics,

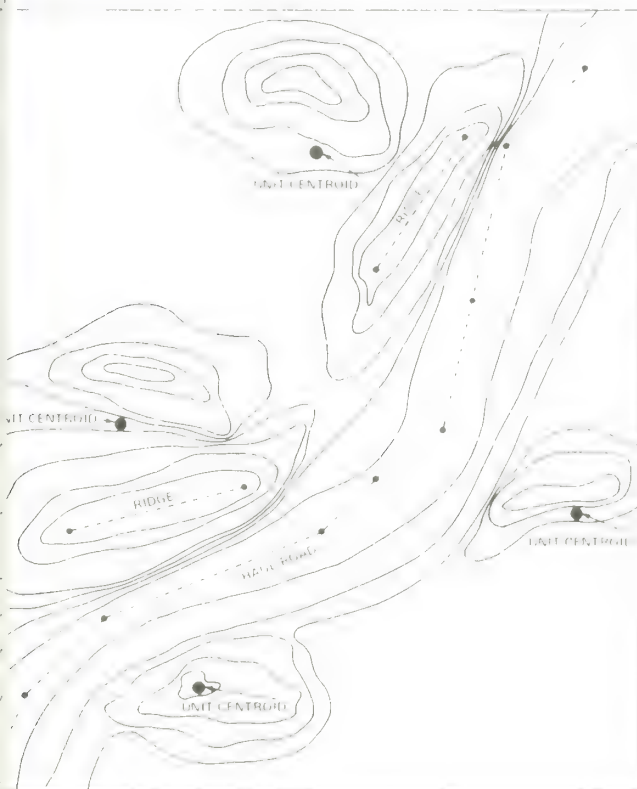
Find:

1. the number of landings,
2. the location of landings on the haul road, and
3. the allocation of logging units to landings,

so as to minimize the sum of:

1. yarding cost,
2. landing construction cost, and
3. hauling cost.

Figure 1 illustrates a helicopter logging layout with four units and a haul road represented by eight linear line segments. On two of the units, ridges may prevent direct flights to landings. The problem is to find the number (1, 2, 3, or 4) and location of landings and the allocation of logging units to landings that will minimize costs.



COMPUTER MODEL

Solution Procedure

A simplified flow chart of the landing location model is given in figure 2. Block 1 represents the input required for solution of the problem. This includes information concerning the units to be logged, the haul road, operating characteristics of the logging system, landing construction, hauling and operating costs, and topographic features of the area.

Block 2 represents the establishment of a scheme for allocating logging units to landings. For example, if three units are to be logged, timber in the first unit may be yarded to one landing and timber in the other two units may be yarded to a second landing. Another allocation scheme would be to yard all timber to one landing. The program has the facility to search all possible allocation schemes or only a particular subset that the user is especially interested in.

Once an allocation scheme is fixed, the program then finds the best location for the specified landings. The program can search along the entire road for these locations or will search only specified points. In either case, it begins the search by fixing a location. This operation is represented by block 3.

Next, flight paths and distances between the units and the landings are determined. When direct flight paths are precluded because of ridges or other obstacles, the flight path is determined to be the shortest distance composed of two linear line segments around the obstacle, as shown in figure 3. (This operation is represented by block 4 in figure 2.). Euclidean distances (including elevation) are used. In a situation similar to that shown in figure 3, since the centroid is used in describing the average flight path, all timber in the unit is routed around the ridge. If the ridge runs through a unit between the road and the centroid, the analyst may wish to define two units, one on each side of the ridge.

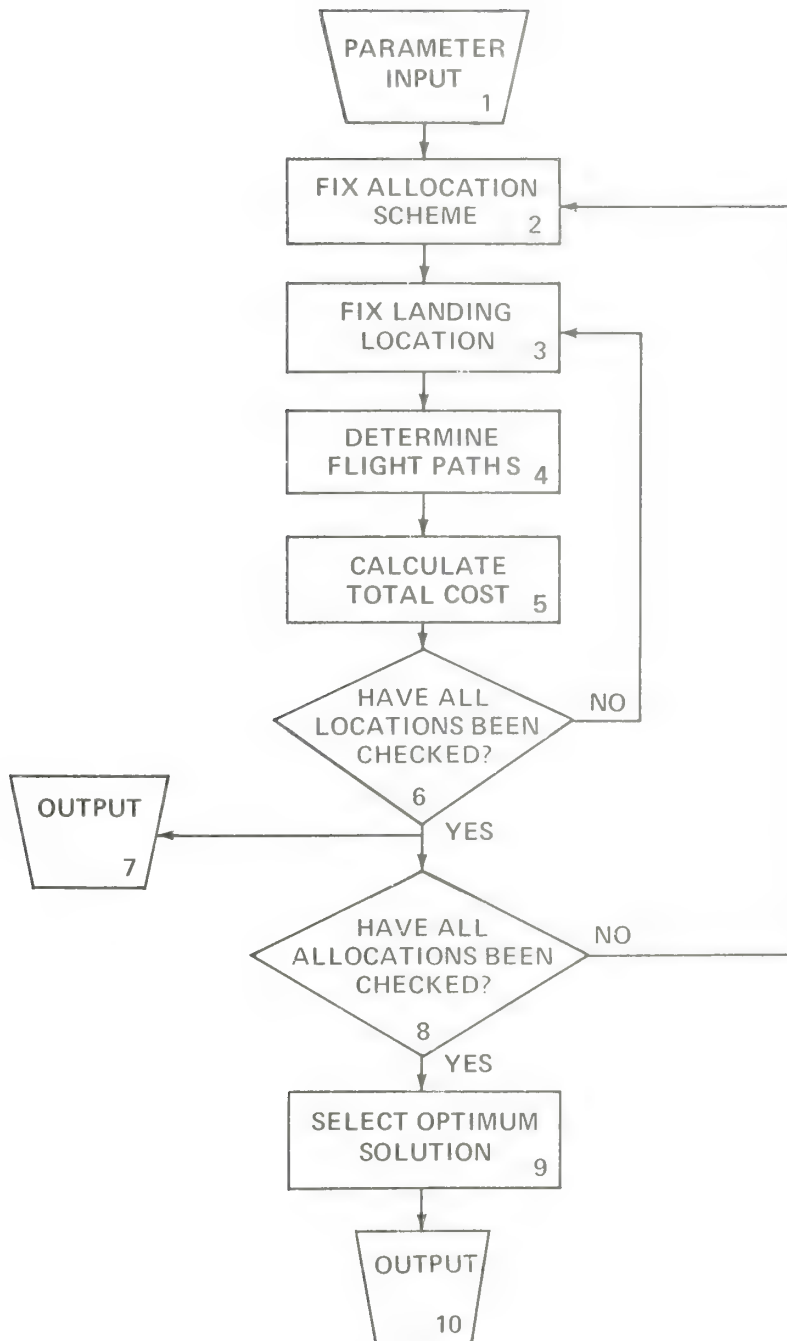


Figure 2.--Simplified flow chart of the location allocation process.

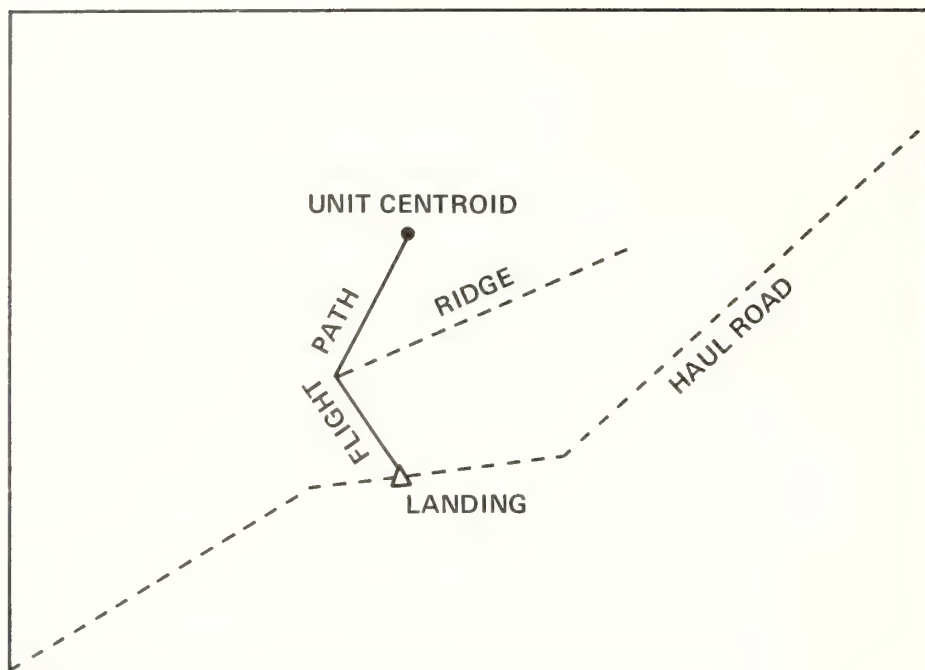


Figure 3.--Helicopter flight path around obstacle.

Total costs for the allocation scheme and location under consideration are then calculated as represented by block 5. Included are yarding costs, landing construction costs, and hauling costs. Abbreviated formulas for each of these are given in figure 4. Yarding costs include the consideration of the average speed of the helicopter when loaded and the average speed when empty. Landing construction costs can vary with location and have both fixed and variable (with weight yarded) components.

Block 6 of figure 2 signifies the program's check to see if all locations have been evaluated; if they have not, the cost of the next location is calculated. The next location can be at a specified increment along the road or at a particular location specified by the user. This process is continued until all locations have been evaluated for a given allocation scheme.

$$\begin{aligned} \text{YARDING COST} &= \sum_{\text{UNITS}} (\text{DISTANCE} \div \text{SPEED} \times \frac{\text{COST}}{\text{TIME}} \times \# \text{ TRIPS}) \\ \text{LANDING CONSTRUCTION COST} &= \sum_{\text{LANDINGS}} (\text{FIXED COST} + \text{VARIABLE COST}) \\ \text{HAULING COST} &= \sum_{\text{LANDINGS}} (\text{DISTANCE} \times \# \text{ TRIPS} \times \frac{\text{COST}}{\text{DISTANCE}}) \end{aligned}$$

Figure 4.--Abbreviated cost equations.

Intermediate output of suboptimum solutions can be obtained as shown by block 7. That is, the program can, at the discretion of the user, print out the best solution for a given allocation scheme.

Once all locations have been evaluated for the current allocation and the minimum cost location has been selected, the program checks to see if all allocation schemes have been examined (block 8). If all schemes have not been evaluated, the process cycles back to block 2; otherwise the optimal solution is selected from previous calculations (block 9). Block 10 represents final output, which may be in several forms at the option of the user, including graphical plotting.

Program Input

The computer program, written in FORTRAN IV, is available on request from the Forestry Sciences Laboratory (ATTN: David F. Gibson), USDA Forest Service, Inter-mountain Forest and Range Experiment Station, P. O. Box 1376, Bozeman, Montana 59715. Input to the program is documented via comments; however, a more thorough explanation follows:

Card Type	Card Col.	Variable	Explanation
Card Set 1: Parameter Cards			
1			
Title Card	1-48	ITITLE	Any 48 alpha-numeric characters can be used to define the title of a particular run. This title will be printed as a heading on output from the line printer and as a caption on plots.
2			
Data Card	1-2	NUNIT	The number of units that are to be logged. (Maximum of 8.)
	3-4	NROAD	The haul road is defined as a set of linear line segments. NROAD is the number of linear line segments representing the road. (Maximum of 20.)
	5-6	NRWL	Certain segments of the road can be defined as infeasible locations for landings. NRWL is the number of such restricted segments. (Maximum of 10.)
	7-16	P	Average weight per load of the helicopter.
	17-26	OC	System operating cost expressed in \$/min.
	27-36	SI	Average speed of helicopter when loaded expressed in ft/min.
	37-46	SO	Average speed of helicopter when unloaded expressed in ft/min.
	47-56	CPM	Cost to haul logs from landing to the mill expressed in \$/mile.
	57-66	WPL	Average weight of truckload expressed in lb.

Card Type	Card Col.	Variable	Explanation
	67-76	XINC	XINC is the increment the program advances along the road in search of the optimum locations. (Expressed in feet.)
	77	IOUT	A variable to control the amount of output of the program. When IOUT = 0, the complete output is printed, which includes input values, the solution for each allocation scheme, and the optimal solution. If IOUT is set equal to 1, a printout of the input values and the optimal solution is made. A printout of only the optimal solution is given when IOUT = 2.
	78	IPLLOT	This variable determines whether the optimal solution is drawn graphically by the CALCOMP plotter. If IPLLOT = 1, a plot is made. If no plot is desired or a CALCOMP plotter is not available, set IPLLOT = 0.
	79-80	NALT	Specific landing locations can be investigated using this variable. If NALT = 0, the road is searched every XINC ft for the best location. Otherwise NALT is the number of alternative landing locations to be tested.

3 This card is required only if IPLLOT on card 2 is 1.

Plot Card	1-2	NCOP	The number of copies of each plot desired.
	3-7	PH	The height in inches of the plot.
	8-12	PW	The width in inches of the plot.

Card Set 2: Unit and Ridge Cards. This card set contains unit and ridge constraint cards. There is one card for each unit. Therefore, there are $I = 1, 2, \dots, \text{NUNIT}$ unit cards in this set. In addition, there is one card for each ridge constraint, but a maximum of one ridge constraint per unit. Ridge constraint cards follow the unit cards for the unit to which they pertain.

1

Unit Card	1-10	UX(I)	X - coordinate of unit I.
	11-20	UY(I)	Y - coordinate of unit I.
	21-30	UZ(I)	Z - coordinate of unit I (elevation).
	31-40	W(I)	Total weight of timber in unit I expressed in lb.
	41	IRC	If unit I has a ridge constraint associated with it, IRC is input as an R and then this card is immediately followed by a ridge constraint card.

Card Type	Card Col.	Variable	Explanation
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2 This card type is required only if an R appears in column 41 of the preceding card.

Ridge Constraint Card	1-10	RCX(I,1)	X - coordinate of beginning of ridge constraint on unit I.
	11-20	RCY(I,1)	Y - coordinate of beginning of ridge constraint on unit I.
	21-30	RCZ(I,1)	Z - coordinate of beginning of ridge constraint on unit I.
	31-40	RCX(I,2)	X - coordinate of end of ridge constraint on unit I.
	41-50	RCY(I,2)	Y - coordinate of end of ridge constraint on unit I.
	51-60	RCZ(I,2)	Z - coordinate of end of ridge constraint on unit I.

Card Set 3: Roadway Cards. This set of cards contains data pertaining to the linear line segments that define the road. This set is not required if NROAD (card set 1, card type 2, columns 3-4) is 0. That is, the program can be run without defining a road. In such a case, NALT would be greater than 0, and the analyst would be investigating a particular set of landing location alternatives.

1

Origin Card	1-10	RX(0)	X - coordinate of beginning point of road.
	11-20	RY(0)	Y - coordinate of beginning point of road.
	21-30	RZ(0)	Z - coordinate of beginning point of road.

2 There must be one of these cards for each linear line segment.

Segment Cards	1-10	RX(I)	X - coordinate of ending point of road segment I.
	11-20	RY(I)	Y - coordinate of ending point of road segment I.
	21-30	RZ(I)	Z - coordinate of ending point of road segment I.
	31-40	FC(I)	Fixed cost of constructing a landing on road segment I expressed in \$.
	41-50	VC(I)	If the cost of a landing on road segment I is also dependent upon the amount of timber yarded to the landing, then the variable VC(I) can be employed to express this cost in terms of \$/lb.

Card Type	Card Col.	Variable	Explanation
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Card Set 4: Restricted Segment Cards. This set of cards defines those segments of the road where it is not possible to construct a landing. IF NRWL (card set 1, card type 2, columns 5-6) is 0, this set is not required. Otherwise there will be NRWL cards in this set, one for each restricted segment.

1

Restricted Segment Cards	1-10	RXL(I,1)	X - coordinate of beginning of restricted segment.
	11-20	RLY(I,1)	Y - coordinate of beginning of restricted segment.
	21-30	RLX(I,2)	X - coordinate of end of restricted segment.
	31-40	RLY(I,2)	Y - coordinate of end of restricted segment.

Card Set 5: Alternative Landing Cards. The card set contains information about specific landing location alternatives the user may want to investigate. This set is not required if NALT (card set 1, card type 2, columns 79-80) is 0. Otherwise there will be NALT cards in this set, one for each alternative landing.

1

Alternative Landing Card	1-10	ALTX(I)	X - coordinate of landing I.
	11-20	ALTY(I)	Y - coordinate of landing I.
	21-30	ALTZ(I)	Z - coordinate of landing I.
	31-40	FC(I)	The fixed cost of constructing a landing at location I expressed in \$.
	41-50	VC(I)	The variable (with amount of timber yarded to the landing) cost of constructing a landing at location I expressed in \$/lb.

Card Set 6: Allocation Scheme Cards. This card set may be repeated as many times as desired by the user, depending upon the number of allocation schemes to be investigated. A new set is required for each different number of landings investigated.

1

Allocation Control Card	1	ID	The variable ID can be set equal to zero (blank) or input as A. If ID = 0, then the second card type will contain allocation matrix cards and the program will search all possible locations on the road for each allocation combination and minimize the total cost in deriving the best solution. If ID = A, the second card type will contain alternative allocation cards, and the program will compare and print the cost of specific location-allocation schemes.
	2-3	NLAND	The number of landings to be employed in the allocation scheme(s) defined in the second card type.
	4-5	NCOM	The number of allocation schemes to follow in the second card type.

Card Type	Card Col.	Variable	Explanation
2			
Allocation Matrix Cards			This type of card is used only if ID = 0 (or blank). If ID = 0 (or blank), there will be NCOM cards of this type. Each allocation scheme will have a card whose entries are the elements of an allocation matrix. Rows represent units and columns represent landings. If unit I is to be assigned to landing J, then the I,J element of the matrix is 1, otherwise it is 0. Entries are read in by column with each entry allotted one card column. These entries can perhaps be best understood by considering the examples presented later in the text and the description given via comment cards in the program.

3			
Alternative Allocation Cards			This type of card is used only if ID = A. If ID = A, there will be NCOM cards of this type. Each allocation combination will have a card which will have NUNIT (number of units to be harvested) entries. The entry in the Ith column will be the alternative landing number to which unit I is to be yarded. These entries can be perhaps best understood by considering the examples presented.

Card Set 7: End of Job. The last card set contains one card, a blank card, which signifies that the problem input is complete. Problems can be run "back to back" by repeating card sets 1 through 7 successively.

Examples

Problem 1

As an example of the use of the model, consider the problem portrayed in figure 1. Figure 5 gives the layout with coordinates, elevations, and other data required for solution. Input to the problem as prescribed in the preceding section is illustrated on a FORTRAN coding sheet in figure 6. Output from the program on the line printer is given as figure 7. Since the input variable "IOUT" (column 77, card 2) was set equal to "0," complete output was obtained. That is, input data, intermediate solutions, and the optimal solution were printed out. The solution for case 7, when two landings are considered, indicates that both landings are in the same location. Since two landings were specified in the allocation scheme, the fixed cost is added twice. However, this solution, relative to location, should then be the same as for the allocation scheme with one landing. Indeed this is the case as indicated in the output. The output obtained from the plotter (obtained because input variable IPLOT, column 78, card 2, was set equal to 1) is shown in figure 8.

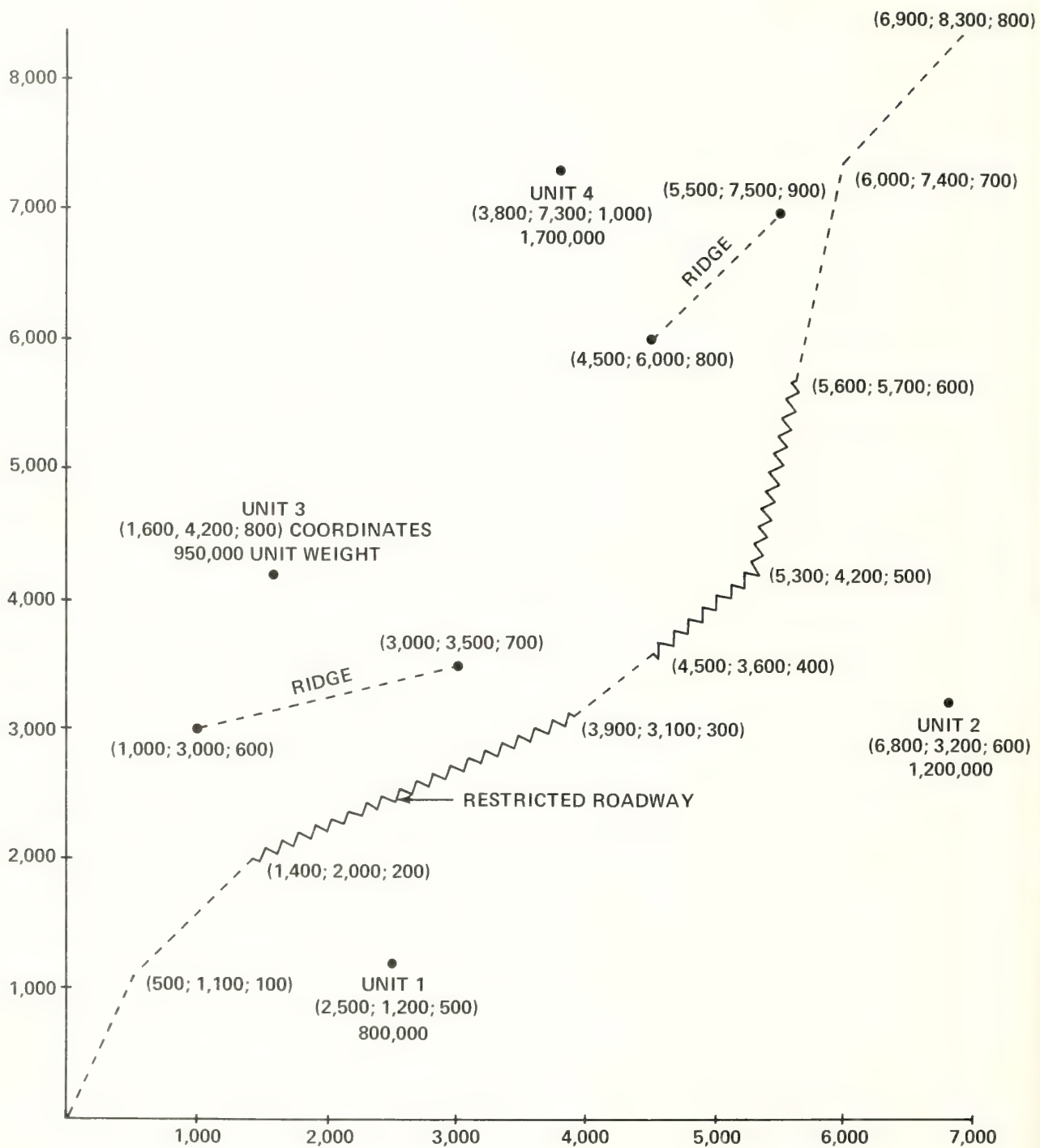


Figure 5.--Layout of helicopter logging problem 1 (from figure 1).

BM

SAMPLE PROBLEM #1				
4 8 2	8000			
1 1 1	8 5			
500.	1200.	500	80	
800	3200.	600	120	
600	4		95	
1000.	3000	600.	3000	
800	7300	1000.	1700000.	
4500.	6000.	800	5500.	
3900.	3100.	300.	1600.	0002
4500.	3600	4	4	
5300	4200.	500	1100.	
5000	5700.			
6000	7400	700.	1	
5900.	8300			
1400.	2000	3900.	3100	
4500.	3600	5600	5700	
4 1				
1000010000100001				
3 6				
100001000001				

BM

01001000001									
001010000010									
011010000001									
101100000010									
01110000100									
1100001									
0110100									
1111000									
1010010									
1000011									
0100100									
0010110									
1 1									
111									
000									

Figure 6.--Input data, for problem #1, problem #2.

Figure 7.--Line printer output, helicopter logging problem 1.

*** PROGRAM PARAMETERS ***

ALMIT ARCAD I.HWL P OC SI SC CPM
4 8 2 .8000E 04 .1800E 02 .3000E C4 .4000E 04 .4000E 00

WPI XINC IOLT IPLCT NALT NCCP PH PW
.6000E C5 .1000E C3 C 1 0 1 11.00 8.50

*** LAIT AND RIDGE CONSTRAINT CARDS ***

I	UX(I)	UY(I)	UZ(I)	W(I)	IRC	RCX(I,1)
1	.250E C4	.120E C4	.500E 03	.800E C6		.000E 00
2	.680E C4	.320E C4	.600E 03	.120E C7		.000E 00
3	.160E C4	.420E C4	.800E 03	.950E C6 R		.100E C4
4	.380E C4	.730E C4	.100E 04	.170E C7 R		.450E 04

RCY(I,1)	RCZ(I,1)	RCX(I,2)	RCY(I,2)	RCZ(I,2)
.000E 00	.000E 00	.000E 00	.000E 00	.000E 00
.000E 00	.000E 00	.000E 00	.000E 00	.000E 00
.300E 04	.600E 03	.300E C4	.350E 04	.700E 03
.800E 04	.800E 03	.550E C4	.750E 04	.900E 03

*** ROADWAY CARDS ***

I	RX(I)	RY(I)	RZ(I)	FC(I)	VC(I)
0	.000E 00	.000E 00	.000E 00		
1	.500E C3	.110E C4	.100E 03	.150E C4	.100E=C3
2	.140E C4	.200E C4	.200E 03	.180E C4	.100E=C3
3	.290E C4	.310E C4	.300E 03	.160E C4	.200E=C3
4	.450E C4	.360E C4	.400E 03	.140E C4	.000E 00
5	.530E C4	.420E C4	.500E 03	.110E C4	.300E=C3
6	.560E C4	.570E C4	.600E 03	.130E C4	.200E=C3
7	.600E C4	.740E C4	.700E 03	.130E C4	.300E=C3
8	.690E C4	.830E C4	.800E 03	.130E C4	.300E=C3

*** RESTRICTED ROADWAY SEGMENTS ***

I	RLX(I,1)	RLY(I,1)	RLX(I,2)	RLY(I,2)
1	.140E C4	.200E C4	.390E C4	.310E C4
2	.450E C4	.360E C4	.560E C4	.570E C4

NUMBER OF UNITS = 4
NUMBER OF LANDINGS = 4

CASE # 1:

LANDING	COORDINATES(X,Y,Z)	UNIT	DISTANCE
#1	(1400, 2000, 200)	#1	1392 FT
#2	(4500, 3600, 400)	#2	2343 FT
#3	(3900, 3100, 300)	#3	2598 FT
#4	(5989, 7354, 697)	#4	2263 FT
YARDING COST = \$ 13443.47			
LANDING BUILDING COST = \$		6429.99	
HALLING COST = \$ 39.89			
TOTAL COST = \$ 19913.36			

NUMBER OF UNITS = 4
NUMBER OF LANDINGS = 3

CASE # 1:

LANDING	COORDINATES(X,Y,Z)	UNIT	DISTANCE
#1	(4437, 3548, 389)	#1	3046 FT
		#2	2397 FT
#2	(3900, 3100, 300)	#3	2598 FT
#3	(5989, 7354, 697)	#4	2263 FT
YARDING COST = \$ 15264.70			
LANDING BUILDING COST = \$			4610.00
HALLING COST = \$ 43.24			
TOTAL COST = \$ 19917.94			

CASE # 2:

LANDING	COORDINATES(X,Y,Z)	UNIT	DISTANCE
#1	(1400, 2000, 200)	#1	1392 FT
		#3	2505 FT
#2	(4500, 3600, 400)	#2	2343 FT
#3	(5989, 7354, 697)	#4	2263 FT
YARDING COST = \$ 13327.89			
LANDING BUILDING COST = \$			5220.00
HALLING COST = \$ 36.61			
TOTAL COST = \$ 18584.50			

CASE # 3:

LANDING	COORDINATES(X,Y,Z)	UNIT	DISTANCE
#1	(4437, 3548, 389)	#1	3046 FT
		#4	3854 FT
#2	(4500, 3600, 400)	#2	2343 FT
#3	(3900, 3100, 300)	#3	2598 FT
YARDING COST = \$ 18728.51			
LANDING BUILDING COST = \$			4260.00
HALLING COST = \$ 34.08			
TOTAL COST = \$ 23022.59			

CASE # 4:

LANDING	COORDINATES(X,Y,Z)	UNIT	DISTANCE
#1	(4437, 3548, 389)	#2	2397 FT
		#3	2940 FT
#2	(1400, 2000, 200)	#1	1392 FT
#3	(5989, 7354, 697)	#4	2263 FT
YARDING COST = \$ 13955.30			
LANDING BUILDING COST = \$			4970.00
HALLING COST = \$ 40.61			
TOTAL COST = \$ 18965.91			

CASE # 5:

LANDING	COORDINATES(X,Y,Z)	UNIT	DISTANCE
#1	(5600, 5700, 600)	#2	2773 FT
		#4	2647 FT
#2	(1400, 2000, 200)	#1	1392 FT
#3	(3900, 3100, 300)	#3	2598 FT
YARDING COST = \$ 14976.89			
LANDING BUILDING COST = \$			5330.00
HALLING COST = \$ 40.08			
TOTAL COST = \$ 20346.97			

CASE # 6:

LANDING COORDINATES(X,Y,Z)		UNIT DISTANCE
#1	(5600, 5700, 600)	#3 4276 FT
		#4 2647 FT
#2	(1400, 2000, 200)	#1 1392 FT
#3	(4500, 3600, 400)	#2 2343 FT
YARDING COST = \$ 16392.63		
LANDING BUILDING COST = \$ 5215.00		
HAULING COST = \$ 40.22		
TOTAL COST = \$ 21747.86		

NUMBER OF UNITS = 4
NUMBER OF LANDINGS = 2

CASE # 1:

LANDING COORDINATES(X,Y,Z)		UNIT DISTANCE
#1	(3900, 3100, 300)	#1 2368 FT
		#2 2917 FT
		#3 2598 FT
#2	(5989, 7354, 697)	#4 2263 FT
YARDING COST = \$ 15372.19		
LANDING BUILDING COST = \$ 3210.00		
HAULING COST = \$ 41.45		
TOTAL COST = \$ 18623.65		

CASE # 2:

LANDING COORDINATES(X,Y,Z)		UNIT DISTANCE
#1	(3900, 3100, 300)	#1 2368 FT
		#3 2598 FT
		#4 4259 FT
#2	(4500, 3600, 400)	#2 2343 FT
YARDING COST = \$ 18919.90		
LANDING BUILDING COST = \$ 2860.00		
HAULING COST = \$ 31.85		
TOTAL COST = \$ 21811.75		

CASE # 3:

LANDING COORDINATES(X,Y,Z)		UNIT DISTANCE
#1	(4437, 3548, 389)	#2 2397 FT
		#3 2940 FT
		#4 3854 FT
#2	(1400, 2000, 200)	#1 1392 FT
YARDING COST = \$ 17504.07		
LANDING BUILDING COST = \$ 3160.00		
HAULING COST = \$ 31.33		
TOTAL COST = \$ 20695.40		

CASE # 4:

LANDING COORDINATES(X,Y,Z)		UNIT DISTANCE
#1	(4437, 3548, 389)	#1 3046 FT
		#2 2397 FT
		#4 3854 FT
#2	(3900, 3100, 300)	#3 2598 FT
YARDING COST = \$ 18813.47		
LANDING BUILDING COST = \$ 2800.00		
HAULING COST = \$ 33.96		
TOTAL COST = \$ 21647.43		

CASE # 5:

LANDING COORDINATES(X,Y,Z)		UNIT DISTANCE
#1	(4437, 3548, 389)	#1 3046 FT
		#2 2397 FT
#2	(5600, 5700, 600)	#3 4276 FT
		#4 2647 FT

YARDING COST = \$ 18213.86
 LANDING BUILDING COST = \$ 3445.00
 HALLING COST = \$ 43.67
 TOTAL COST = \$ 21702.43

CASE # 6:

LANDING COORDINATES(X,Y,Z)	UNIT DISTANCE
#1 (1400, 2000, 200)	#1 1392 FT
	#3 2505 FT
#2 (5600, 5700, 600)	#2 2773 FT
	#4 2647 FT

YARDING COST = \$ 14861.31
 LANDING BUILDING COST = \$ 4120.00
 HALLING COST = \$ 36.80
 TOTAL COST = \$ 19018.11

CASE # 7:

LANDING COORDINATES(X,Y,Z)	UNIT DISTANCE
#1 (4437, 3548, 389)	#1 2046 FT
	#4 3854 FT
#2 (4437, 3548, 389)	#2 2397 FT
	#3 2940 FT

YARDING COST = \$ 19240.34
 LANDING BUILDING COST = \$ 2800.00
 HALLING COST = \$ 34.80
 TOTAL COST = \$ 22075.14

NUMBER OF UNITS = 4
 NUMBER OF LANDINGS = 1

CASE # 1:

LANDING COORDINATES(X,Y,Z)	UNIT DISTANCE
#1 (4437, 3548, 389)	#1 3046 FT
	#2 2397 FT
	#3 2940 FT
	#4 3854 FT

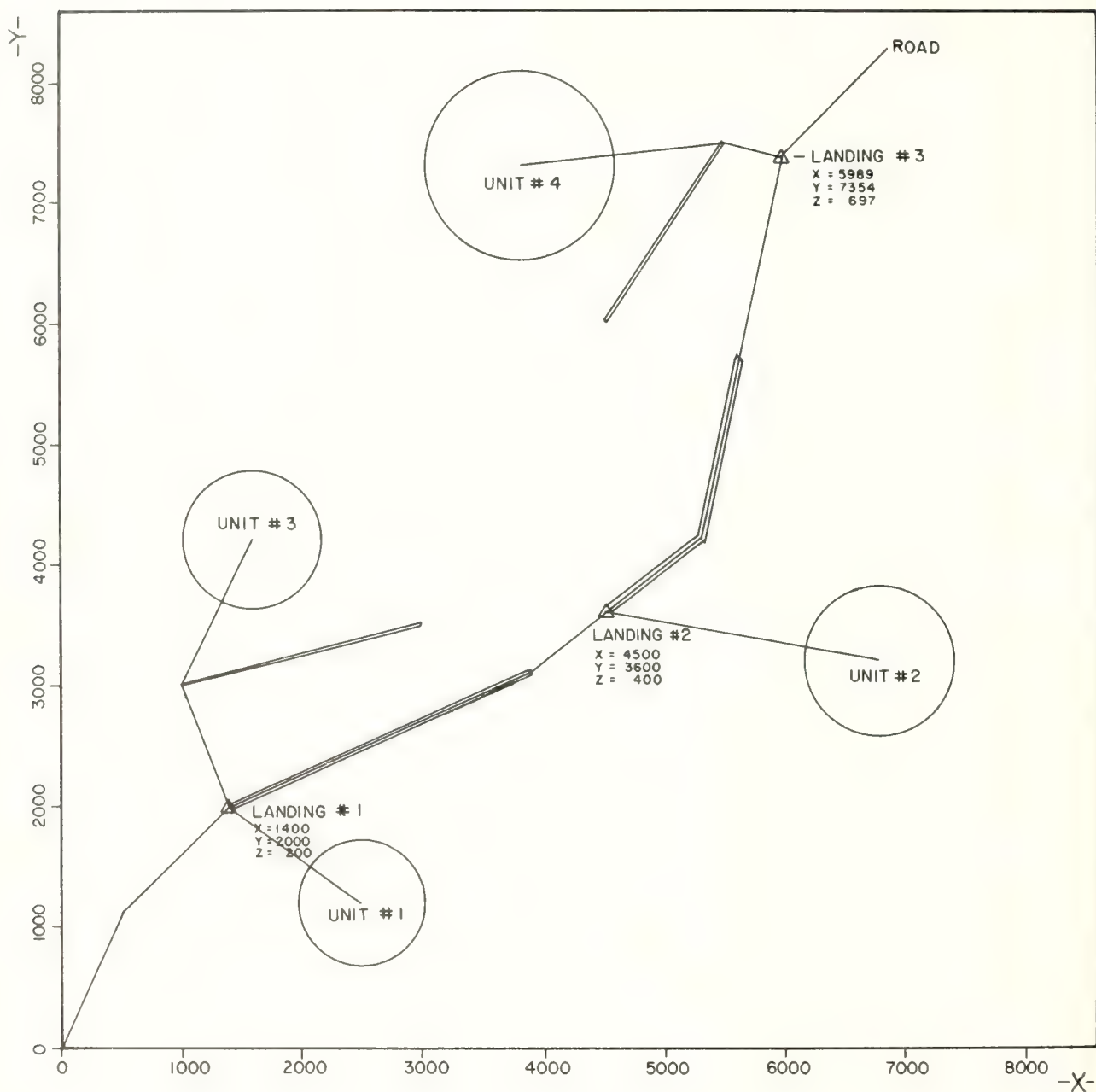
YARDING COST = \$ 19240.34
 LANDING BUILDING COST = \$ 1400.00
 HALLING COST = \$ 34.80
 TOTAL COST = \$ 20675.14

 *
 * LANDING LOCATION MODEL *
 * BEST SOLUTION *
 *

NO OF UNITS = 4
 NO OF LANDINGS = 3

LANDING COORDINATES(X,Y,Z)	UNIT DISTANCE
#1 (1400, 2000, 200)	#1 1392 FT
	#3 2505 FT
#2 (4500, 3600, 400)	#2 2343 FT
#3 (5989, 7354, 697)	#4 2263 FT

YARDING COST = \$ 13327.89
 LANDING BUILDING COST = \$ 5220.00
 HALLING COST = \$ 36.61
 TOTAL COST = \$ 18584.50



HELICOPTER LANDING LOCATION MODEL EXAMPLE PROBLEM #1

Figure 8.--Plotter output, helicopter logging problem 1.

Problem 2

In problem 1, the variable NALT (columns 79-80, card 2) was set to 0. Thus the program considered locations along the entire road in 100-foot increments (variable XINC, column 67-76, card 2) for potential landing locations. In problem 2, let us suppose that the analyst wished to consider only five specific locations on the road as possible alternatives. The alternative locations, and their respective landing building costs are given in table 1. Now evaluate several different allocation schemes; first, various allocation schemes utilizing two landings, and also four schemes utilizing three landings. These schemes are shown in table 2. Input format for this problem is illustrated on a FORTRAN coding sheet in figure 9. It should be noted that NALT (column 80, card 2) is now set equal to 5. Also note that landing costs do not have to be included on roadway cards since these costs are now associated with specific landings. Output of example problem 2 is given in figures 10 and 11 for the line printer and plotter, respectively.

Table 1.--Alternative landing data

Alternative	Coordinates	Fixed Cost	Variable Cost
1	(1,400; 2,000; 200)	1,600	0.0002
2	(4,500; 3,600; 400)	1,100	.0003
3	(5,600; 5,700; 600)	1,300	.0005
4	(6,000; 7,400; 700)	1,300	.0003
5	(6,450; 7,850; 750)	1,300	.0003

Table 2.--Specific allocation schemes with three landings

Scheme	Landing	Unit
1	1	1,3
	3	4
	5	2
2	2	1,3
	4	4
	5	2
3	1	1
	2	2
	3	3,4
4	1	3
	2	1,2
	4	1

FORTRAN STATEMENT									
EXAMPLE	PROBLEM	# 2							
4	8	2	8000.	18.	3000.	4000.	40	60000.	100.01 5
1	11	8.5							
	500.	1200.	500.	800000.					
	800.	3200.	600.	1200000.					
	1600.	4200.	800.	950000.	R				
	1000.	3000.	600.	3000.		3500.	700.		
	3800.	7300.	1000.	1700000.	R				
	4500.	6000.	800.	5500.		7500.	900.		
	0.	0.	0.						
	500.	1100.	100.						
	1400.	2000.	200.						
	3900.	3100.	300.						
	4500.	3600.	400.						
	5300.	4200.	500.						
	5600.	5700.	600.						
	6000.	7400.	700.						
	5900.	8300.	800.						
	1400.	2000.	3900.	3100.					
	4500.	3600.	5600.	5700.					
	1400.	2000.	200.	1600.		0002			
	4500.	3600.	400.	1100.		.0003			
	5600.	5700.	600.	1300.		.0003			
	6000.	7400.	700.	1300.		.0003			

FORTRAN STATEMENT									
	6450.	7850.	750.	1300.	.0003				
2 5									
11100001									
01111000									
11010010									
11000011									
10100101									
A 3 4									
1513									
2524									
1233									
2214									
0000									

Figure 9.--Input data, helicopter logging problem 2.

Figure 10.--Line printer output, *in the form of a printout*.

**** PROGRAM PARAMETERS ****

ALMIT	ARCAD	ARWL	P	OC	SI	SC	CRK
4	8	2	.8000E 04	.1200E 02	.3000E 04	.4000E 04	.4000E 04

WPL	XINC	IOLT	IPLOT	NALT	NCCF	PH	PR
.6000E 05	.1000E 03	0	1	5	1	11.00	8.50

**** UNIT AND RIDGE CONSTRAINT CARDS ****

I	LX(I)	LY(I)	LZ(I)	W(I)	INC	RCX(I,1)
1	.250E 04	.120E 04	.500E 03	.800E 06		.000E 00
2	.680E 04	.320E 04	.600E 03	.120E 07		.000E 00
3	.160E 04	.420E 04	.800E 03	.950E 06	R	.100E 04
4	.320E 04	.730E 04	.100E 04	.170E 07	R	.450E 04

RCY(I,1)	RCZ(I,1)	RCX(I,2)	RCY(I,2)	RCZ(I,2)
.000E 00	.000E 00	.000E 00	.000E 00	.000E 00
.000E 00	.000E 00	.000E 00	.000E 00	.000E 00
.300E 04	.600E 03	.300E 04	.350E 04	.700E 03
.700E 04	.800E 03	.550E 04	.750E 04	.900E 03

**** ROADWAY CARDS ***

I	RX(I)	RY(I)	RZ(I),	FC(I)	VC(I)
0	.000E 00	.000E 00	.000E 00		
1	.500E 03	.110E 04	.100E 03	.000E 00	.000E 00
2	.140E 04	.200E 04	.200E 03	.000E 00	.000E 00
3	.390E 04	.310E 04	.300E 03	.000E 00	.000E 00
4	.450E 04	.360E 04	.400E 03	.000E 00	.000E 00
5	.530E 04	.420E 04	.500E 03	.000E 00	.000E 00
6	.560E 04	.570E 04	.600E 03	.000E 00	.000E 00
7	.600E 04	.740E 04	.700E 03	.000E 00	.000E 00
8	.690E 04	.830E 04	.800E 03	.000E 00	.000E 00

*** RESTRICTED ROADWAY SEGMENTS ***

I	RLX(I,1)	RLY(I,1)	RLX(I,2)	RLY(I,2)
1	.140E C4	.200E C4	.390E C4	.310E C4
2	.450E C4	.360E C4	.560E C4	.570E C4

*** ALTERNATIVE LANDING LOCATIONS ***

I	ALT(X(I))	ALT(Y(I))	ALT(Z(I))	FC(I)	VC(I)
1	.140E C4	.200E C4	.200E C3	.160E C4	.200E=C3
2	.450E C4	.360E C4	.400E C3	.110E C4	.300E=C3
3	.560E C4	.570E C4	.600E C3	.130E C4	.300E=C3
4	.600E C4	.740E C4	.700E C3	.130E C4	.300E=C3
5	.645E C4	.785E C4	.750E C3	.130E C4	.300E=C3

NUMBER OF UNITS = 4
NUMBER OF LANDINGS = 2

CASE # 1:

LANDING	COORDINATES(X,Y,Z)	UNIT	DISTANCE
#2	(.4500, .3600, .400)	#1	3125 FT
		#2	2343 FT
		#3	2988 FT
#4	(.6000, .7400, .700)	#4	2262 FT
YARDING COST = \$		15746.26	
LANDING BUILDING COST = \$		3795.00	
TOTAL COST = \$		19541.25	

CASE # 2:

LANDING	COORDINATES(X,Y,Z)	UNIT	DISTANCE
#3	(.5600, .5700, .600)	#2	2773 FT
		#3	4276 FT
		#4	2647 FT
#1	(.1400, .2000, .200)	#1	1392 FT
YARDING COST = \$		17069.90	
LANDING BUILDING COST = \$		4215.00	
TOTAL COST = \$		21284.89	

CASE # 3:

LANDING	COORDINATES(X,Y,Z)	UNIT	DISTANCE
#2	(.4500, .3600, .400)	#1	3125 FT
		#2	2343 FT
		#4	3813 FT
#1	(.1400, .2000, .200)	#3	2505 FT
YARDING COST = \$		18604.26	
LANDING BUILDING COST = \$		4000.00	
TOTAL COST = \$		22604.25	

CASE # 4:

LANDING	COORDINATES(X,Y,Z)	UNIT	DISTANCE
#2	(4500, 3600, 400)	#1	3125 FT
		#2	2343 FT
#3	(5600, 5700, 600)	#3	4276 FT
		#4	2647 FT

YARDING COST = \$ 18212.14
 LANDING BUILDING COST = \$ 3795.00
 TOTAL COST = \$ 22007.13

CASE # 5:

LANDING	COORDINATES(X,Y,Z)	UNIT	DISTANCE
#1	(1400, 2000, 200)	#1	1392 FT
		#3	2505 FT
#3	(5600, 5700, 600)	#2	2773 FT
		#4	2647 FT

YARDING COST = \$ 14861.31
 LANDING BUILDING COST = \$ 4120.00
 TOTAL COST = \$ 18981.31

NUMBER OF UNITS = 4
 NUMBER OF ALTERNATIVE LANDINGS = 5

CASE # 1:

UNIT	ALTERNATIVE	COORDINATES(X,Y,Z)	DISTANCE
#1	#1	(1400, 2000, 200)	1392 FT
#2	#5	(6450, 7850, 750)	4665 FT
#3	#1	(1400, 2000, 200)	2505 FT
#4	#3	(5600, 5700, 600)	2647 FT

YARDING COST = \$ 17841.96
 LANDING BUILDING COST = \$ 5419.99
 TOTAL COST = \$ 23261.95

CASE # 2:

UNIT	ALTERNATIVE	COORDINATES(X,Y,Z)	DISTANCE
#1	#2	(4500, 3600, 400)	3125 FT
#2	#5	(6450, 7850, 750)	4665 FT
#3	#2	(4500, 3600, 400)	2988 FT
#4	#4	(6000, 7400, 700)	2262 FT

YARDING COST = \$ 19404.17
 LANDING BUILDING COST = \$ 5094.99
 TOTAL COST = \$ 24499.16

CASE # 3:

UNIT	ALTERNATIVE	COORDINATES(X,Y,Z)	DISTANCE
#1	#1	(1400, 2000, 200)	1392 FT
#2	#2	(4500, 3600, 400)	2343 FT
#3	#3	(5600, 5700, 600)	4276 FT
#4	#3	(5600, 5700, 600)	2647 FT

YARDING COST = \$ 16392.63
LANDING BUILDING COST = \$ 5314.99
TOTAL COST = \$ 21707.62

CASE # 4:

UNIT	ALTERNATIVE	COORDINATES(X,Y,Z)	DISTANCE
#1	#2	(4500, 3600, 400)	3125 FT
#2	#2	(4500, 3600, 400)	2343 FT
#3	#1	(1400, 2000, 200)	2505 FT
#4	#4	(6000, 7400, 700)	2262 FT

YARDING COST = \$ 15144.11
LANDING BUILDING COST = \$ 5299.99
TOTAL COST = \$ 20444.10

*
* LANDING LOCATION MODEL *
* BEST SOLUTION *
*

* * * * *

* NO OF UNITS = 4 * *

* NO OF LANDINGS = 2 * *

* * * * *

* *****

LANDING	COORDINATES(X,Y,Z)	UNIT	DISTANCE
---------	--------------------	------	----------

#1	(1400, 2000, 200)	#1	1392 FT
----	--------------------	----	---------

		#3	2505 FT
--	--	----	---------

#3	(5600, 5700, 600)	#2	2773 FT
----	--------------------	----	---------

		#4	2647 FT
--	--	----	---------

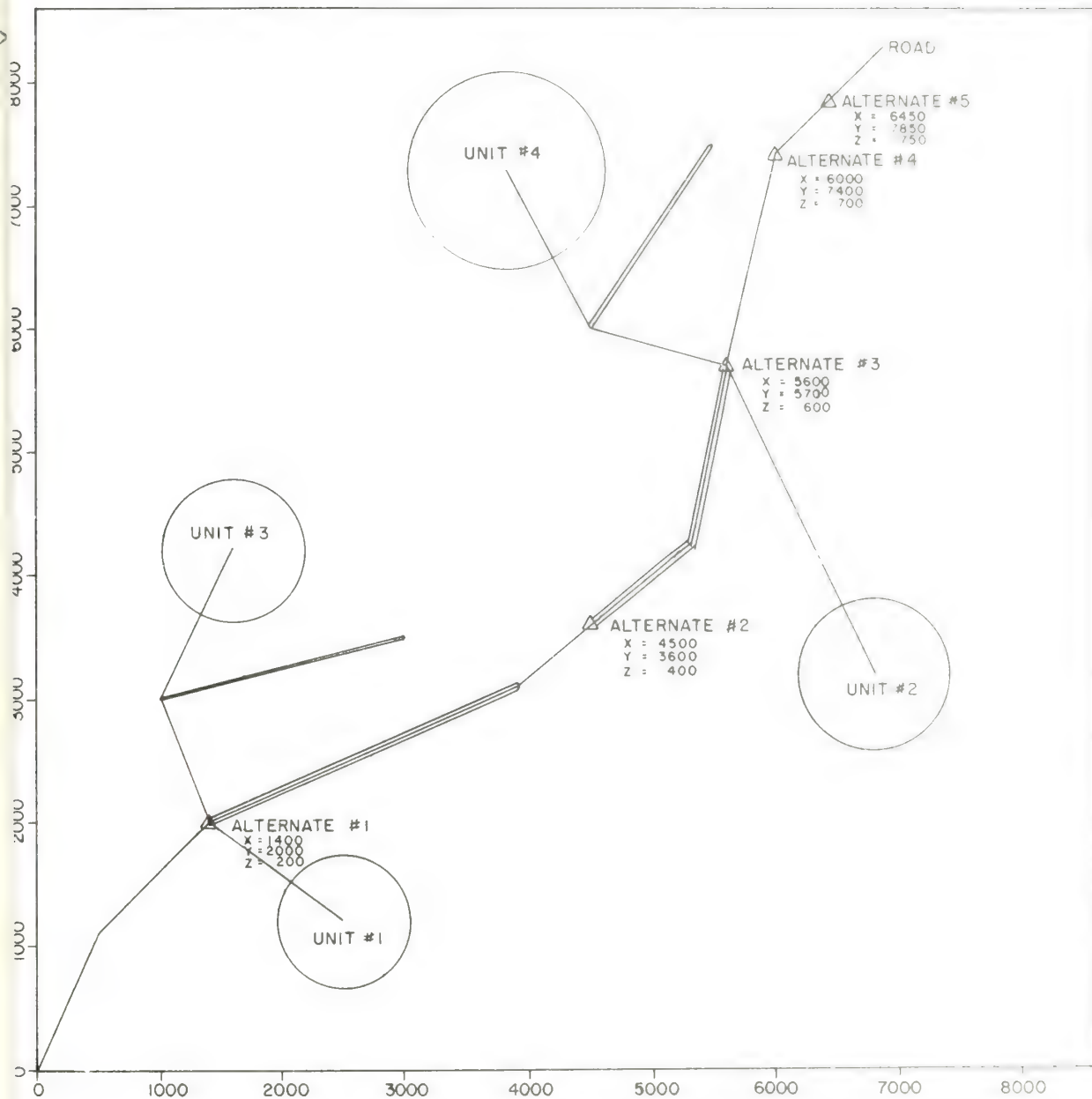
YARDING COST = \$ 14861.31 * *

LANDING BUILDING COST = \$ 4120.00 * *

TOTAL COST = \$ 18981.31 * *

* * * * *

STOP C



HELICOPTER LANDING LOCATION MODEL EXAMPLE PROBLEM #2

Figure 11.--Plotter output, helicopter logging problem 2.

Limitations

Limitations of the program with respect to the number of critical parameters are:

<i>Parameter</i>	<i>Maximum</i>
Number of units	8
Number of road segments	20
Number of restricted road segments	10
Ridges	1/unit

The first three limitations shown are imposed primarily to conserve storage requirements and can be easily increased. The fourth limitation is the number of ridge constraints that can be considered per unit. Presently, the program is limited to, at most, one ridge constraint per unit (units may have a common constraining ridge). This limitation cannot be altered easily, as a change would entail additional programming. Present capabilities will prove adequate for most helicopter logging sales.

When evaluating specific alternative landings ($NALT > 0$), hauling costs are not calculated. Under this option, landings need not be located on an existing road, therefore actual hauling costs may be unknown until the location and cost are specified for a spur road from the haul road to the landing. As shown by the preceding examples, however, these costs generally prove to be very small as compared to landing and yarding costs.

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EGGING, LOUIS T., and DAVID F. GIBSON

1974. Helicopter logging: a model for locating landings. USDA For. Serv. Res. Pap. INT-155, 27 p., illus. (Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.)

Presented are a model and an accompanying computer program that optimally locate landing areas for a helicopter logging operation. Given a haul road, unit centroids, volumes of timber to be harvested, and helicopter operating parameters, landings are located so as to minimize yarding, hauling, and landing construction costs. The model considers constraints such as areas that are not suitable for landings and topographical obstacles. Written in FORTRAN IV, the computer program affords several evaluation and output options. Two examples are provided.

OXFORD: 376:30.

KEYWORDS: helicopter logging, landing location, optimization.

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Headquarters for the Intermountain Forest and
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Field Research Work (Partners: montanomedica)

Boise, Idaho

Bozeman, Montana (in cooperation with
Montana State University)

Logan, Utah (in cooperation with Utah
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University of Montana)

Moscow, Idaho (in cooperation with the
University of Idaho)

Provo, Utah (in cooperation with Brigham
Young University)

Reno, Nevada (in cooperation with the
University of Nevada)

EROSION OVER TIME ON SEVERELY DISTURBED GRANITIC SOILS: A MODEL

W. E. Megahan

USDA Forest Service
Forest Sciences Laboratory, Forest Sciences Center,
Forest Sciences Building, 2000 SW Jefferson Way, Corvallis,
OR 97331, U.S.A.

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THE AUTHOR

WALTER F. MEGAHAN is Principal Research Hydrologist and Leader of the Idaho Batholith Ecosystems Research Work Unit in Boise, Idaho. He holds bachelor's and master's degrees in Forestry from the State University of New York, College of Forestry, at Syracuse University, and a doctoral degree in Watershed Resources from Colorado State University. He served as Regional Hydrologist for the Intermountain Region of the USDA Forest Service in Ogden, Utah, from 1960 to 1966 and has been in his present position since 1967.

USDA Forest Service
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EROSION OVER TIME ON SEVERELY DISTURBED GRANITIC SOILS: A MODEL

W. F. Megahan

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Roger R. Bay, Director

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ABSTRACT

A negative exponential equation containing three parameters was derived to describe time trends in surface erosion on severely disturbed soils. Data from four different studies of surface erosion on roads constructed from the granitic materials found in the Idaho Batholith were used to develop equation parameters. Rainfall-intensity data were used to illustrate that variations in erosion forces, as indexed by rainfall kinetic energy times the maximum 30-minute rainfall intensity (the erodibility index), were not the cause of the time trend in surface erosion. In addition, although vegetation growth can be an important factor in reducing accelerated erosion, it did not cause the rapid erosion decreases found in the cases studied. The evidence suggests that surface "armoring" was the dominant factor causing the time trends in surface erosion. The significance of time trends in surface erosion is discussed.

INTRODUCTION

Surface erosion can be defined as movement of individual soil particles along the soil surface, in contrast to mass erosion, the movement en masse of numerous particles. The subject of this paper, surface erosion, can be expressed as

$$\epsilon = f(h, p, f), \quad (1)$$

where ϵ = surface erosion rate; h = inherent soil erosion hazard and includes such factors as soil detachability and slope gradient; p = protection afforded the soil surface by vegetation and litter; and f = force applied by raindrops, overland flow, etc.

Under a relatively stable forest ecosystem, erosion hazards tend to be minimized and protection afforded the soil surface tends to be maximized. Erosion forces vary but, over time, yield some average (or other appropriate measure of central tendency) value for surface erosion, which varies with individual site conditions. This average erosion rate (ϵ_n) has been termed the "norm" for the site in question (Bailey 1941).

Severe soil disturbance disrupts the ecological balance, thereby increasing h and decreasing p . Consequently, surface erosion rates are accelerated, often to alarming proportions (Anderson 1954; Reinhart and others 1963; Packer 1967; Copeland and Packer 1972). Over time, a new ecological balance is established on the disturbed site that leads to a new erosion norm, which may differ from the original because of permanent changes in site factors. Thus, on a severely disturbed site, the total erosion rate at any time (ϵ_t) is comprised of two components, the natural norm for the site (ϵ_n) plus the accelerated erosion due to disturbance (ϵ_s). Therefore,

$$\epsilon_t = \epsilon_n + \epsilon_s \quad (2)$$

Considering the accelerated erosion component (ϵ_s), a body of disturbed soil, (S) can be assumed, where disturbance has been severe enough to completely disrupt the original soil characteristics. Such soil is a polydispersed mixture with subsoil and bedrock fragments well graded throughout, with no remnants of the original soil horizons or structural development, and with no surface vegetation or litter. Such disturbances have numerous causes such as road construction, mining, logging, and landslides.

Relation 1 above reduces to

$$\epsilon_s = f(h) \quad (3)$$

if it is assumed that f is constant and p is zero (i.e., there is no protection available from vegetation, litter, mulches, etc.). Under such conditions, it is logical to assume that the opportunity for erosion is maximum immediately after disturbance and decreases with time. In other words, the erosion hazard decreases with time after disturbance. A number of causal factors might exist. For example, in a polydispersed mixture, the more easily detached and transported particles are most likely to be removed first. Over time, the average erodibility of the surface materials will tend to decrease. This "armoring" or "erosion pavement" phenomenon is commonly observed and is probably the result of an increase in the average size of surface particles, possibly, keying in of surface particles (fig. 1), or both. Other factors, such as compaction of materials as settling occurs and reduction in slope gradients, may also help reduce erosion hazards over time.

If erosion hazards do indeed decrease following disturbance and relation 3 is valid, the rate of accelerated erosion can be assumed to be directly proportional to erosion hazard ($\epsilon_s \propto h$). Further, erosion hazard is greatest when the disturbed soil body is greatest and decreases as the body of soil decreases. Thus, erosion hazard appears to be directly proportional to the amount of soil present ($h \propto S$). Assuming linearity, constants of proportionality can be assigned to the above proportions,

$$\epsilon_s = k_1 h$$

$$h = k_2 S;$$

so
$$\epsilon_s = k_1 k_2 S = kS.$$

But, ϵ_s is simply the rate of change of S ,

$$\epsilon_s = \frac{ds}{dt}; \quad (4)$$

so
$$\frac{ds}{dt} = -kS. \quad (5)$$

The negative constant of proportionality is used to indicate soil loss. By solving for S and integrating,

$$S = S_0 e^{-kt},$$

based on the boundary condition that $S = S_0$ when $t = 0$. Substituting in 4 and 5,

$$\epsilon_s = -kS_0 e^{-kt}. \quad (6)$$



Figure 1.--Photograph A was taken on a road fill on Interstate 90 in northern Idaho shortly after construction. The same plot is shown in photograph B, 4 months later. Note the increase in average surface particle size resulting from erosion.

In this form, ϵ_g represents a loss from the body of soil S and so is a negative value. However, this is not consistent with equation 2 where ϵ_s is positive. Thus, equation 6 is modified to:

$$\epsilon_s = kS_0e^{-kt} \quad (7)$$

Finally, when equation 7 is substituted into equation 2, the total erosion rate on a disturbed site is

$$\epsilon_t = \epsilon_n + kS_0e^{-kt}, \quad (8)$$

where ϵ_n , S_0 and k are parameters to be determined.

Interpretations of these parameters and the units used in this report are:

$\epsilon_n(\text{tons mi}^{-2}\text{day}^{-1})$ = The erosion rate to be expected on the disturbed area after a long period, assuming no new major disturbance. This value is an estimate of the long-term norm for the site.

$S_0(\text{tons mi}^{-2})$ = the amount of material available to be eroded at time zero after disturbance.

$k(\text{day}^{-1})$ = an index of the rate of decline of erosion following disturbance. This can be thought of as an index of the recovery potential for the site in question.

By measuring erosion rates on disturbed sites over time, values can be assigned to these parameters. However, measurements of instantaneous erosion rates are extremely difficult to obtain. Most studies of erosion depend upon periodic measurements of on-site soil losses or of accumulations of eroded material at some downslope point. Such data provide a measure of erosion integrated over time. Accordingly, equation 8 must be integrated in order to develop parameter estimates from periodic measurements of erosion. Integration of equation 8 with respect to time yields the model to be fitted,

$$\epsilon_t = \epsilon_n t - S_0[e^{-kt} - 1], \quad (9)$$

where ϵ_t is in units of tons mi^{-2} and t is the days of elapsed time since disturbance.

EXPERIMENTAL RESULTS

The Forest Service has been studying the effects of severe soil disturbance on surface erosion and sedimentation in the Idaho Batholith for a number of years. The Idaho Batholith is an extensive mass of granitic rock (16,000 mi²) covering a large portion of Idaho and parts of Montana (fig. 2). Various types of granitic rocks are found; however, quartz monzonite predominates. The bedrock exhibits wide variation in degree of weathering and fracturing (Clayton and Arnold 1972). The area is almost entirely mountainous and forested. Typically, shallow, coarse-textured soils are found on steep slopes that often exceed 70 percent gradient. Soils of this type are extremely erodible (Anderson 1954; André and Anderson 1961). Localized, high-intensity rainstorms of short duration are common during the summer season. At other times of the year more general storms occur, often in conjunction with melting snowpacks. Following soil disturbance, the combination of steep topography, high-soil erodibility, and high-climatic stress often results in dramatically accelerated surface erosion rates (Megahan and Kidd, 1972).

Data available from four different studies (fig. 2) conducted in the Idaho Batholith provide insight into the time trends in surface erosion following road construction. Two studies in the Deep Creek and Silver Creek study areas present data for erosion from the entire road prism (cut slopes + roadbed + fill slopes). The other two studies, located on double-lane forest roads in the Bogus Basin and Deadwood River areas, were designed to measure erosion on road fill slopes only.

Road Prism Erosion

Deep Creek Study:--In the Deep Creek study (fig. 2), about 0.2 mile (providing a total area disturbed of 1.1 acres) of low-standard logging-access roads was constructed in two small, ephemeral drainages totaling 5.2 acres. Slope gradients in the drainages average about 70 percent. Material eroded from the entire road prism was trapped in sediment dams located about 300 feet downslope. Data from the sediment dams were collected twice a year: following the snowmelt period (about June 1) and near the end of



Figure 2.--Location of study sites in the Idaho Batholith.

the water year (about September 30). Sediment accumulations behind the dams were surveyed by using a grid of closely spaced cross sections. The study was designed so that road erosion could be segregated from erosion occurring on unroaded portions of the drainages (Megahan and Kidd 1972). The roads were constructed in November 1961; collection of postconstruction data was continued on schedule until September 1967. Twelve measurement periods were sampled during the 6-year study.

Accumulated surface erosion data are plotted in figure 3. Notice that eroded material accumulates rapidly immediately after disturbance, but that the rate of accumulation decreases with time. Equation 9 was fitted to the data by using a nonlinear least-squares procedure (Marquardt 1963). The fitted regression line and the derived equation are shown on figure 3. The relation has a standard error of 502 tons mi⁻² and an r² value of 0.98. Nonlinear confidence limits for model parameters indicate that all parameters are significantly greater than zero at the 95 percent level.

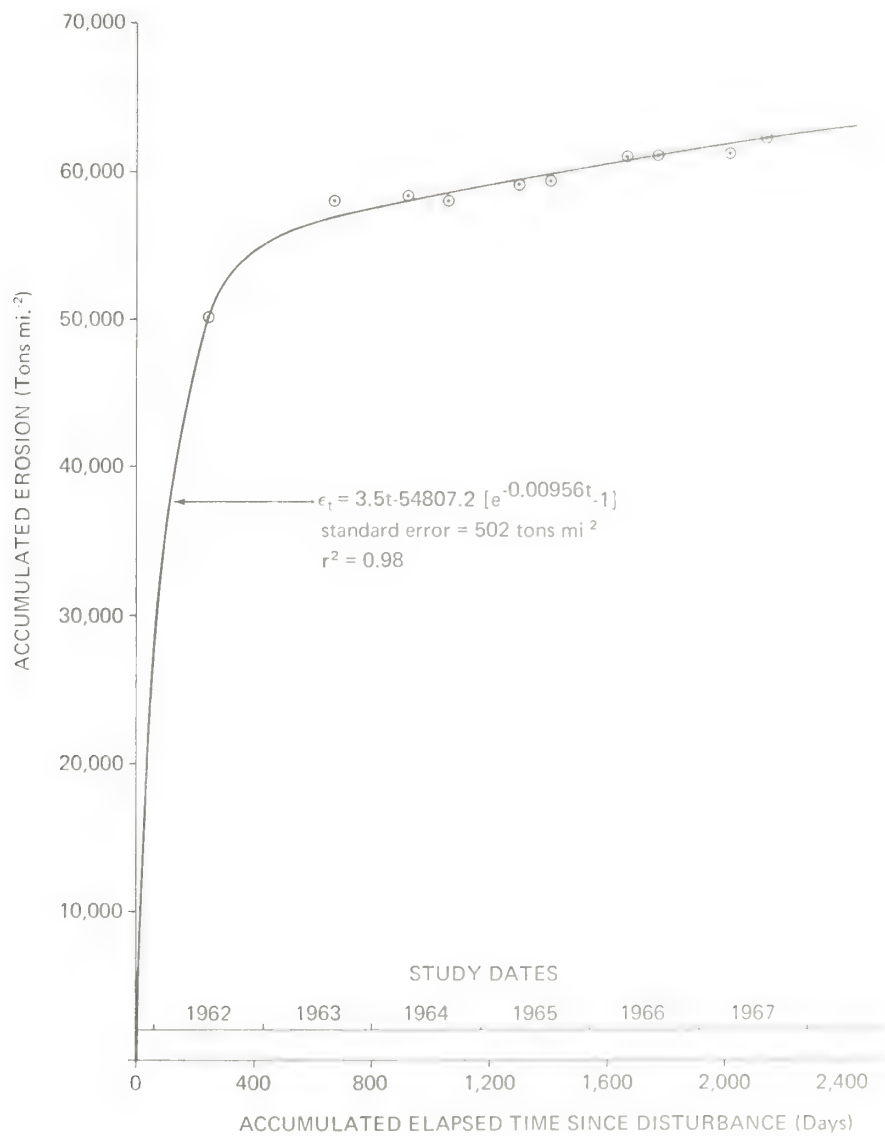


Figure 3.--Accumulated surface erosion over time--Deep Creek Study area.

Silver Creek Study:--Other study data are available to check the validity of the long-term erosion rate (ϵ_n) determined from the Deep Creek data. Beginning in 1965, annual sediment production data have been collected from each of seven study watersheds in the Silver Creek area of the Payette River drainage (fig. 2). Six of the study watersheds are essentially undisturbed; the seventh, Ditch Creek, contains a low-standard forest road about 2 miles long that was constructed in 1933. The road is comparable to the Deep Creek road in that it is low standard, narrow, closely fitted to the landscape, and traverses similar topography for most of its length.

Average sediment yields for Ditch Creek are greater than for any other watershed in the Silver Creek study area. However, based on watershed characteristics, Ditch Creek should rank approximately in the middle of the seven watersheds in terms of sediment production. No doubt, the increased sediment yields in Ditch Creek are due to erosion on the Ditch Creek road. This statement is borne out by inspection on the ground; erosion is occurring on the road tread, on the cut slopes, and in isolated instances on the fill slopes (Megahan 1972).

Logically, the undisturbed sediment yields from the 0.41-mi² Ditch Creek drainage would fall between the sediment yields from the two watersheds that flank it (Cabin Creek, 0.40 mi², and Eggers Creek, 0.51 mi²), because it is intermediate in respect to forest cover, sideslope gradient, channel gradient, and watershed size. Thus, the average of sediment yields from the two undisturbed drainages provides a reasonable estimate of what the sediment yield for Ditch Creek would be if the watershed were in the undisturbed state. This amount can be subtracted from the measured sediment yield to obtain an estimate of the sediment yield caused by the old road. Finally, this amount can be prorated back to the area actually disturbed by road construction to provide a measure of annual road erosion. Based upon 7 years of data, annual road erosion ranges from 0.4 to 9.7 tons mi⁻² day⁻¹ and averaged 3.5 tons mi⁻² day⁻¹. The average erosion rate for this 37-year-old road is equal to the value of ϵ_n derived from the Deep Creek study. Such values would be expected to vary with site conditions. Consequently, such good agreement is likely to be more coincidence than fact, but it does illustrate that the ϵ_n value predicated from the Deep Creek study is reasonable.

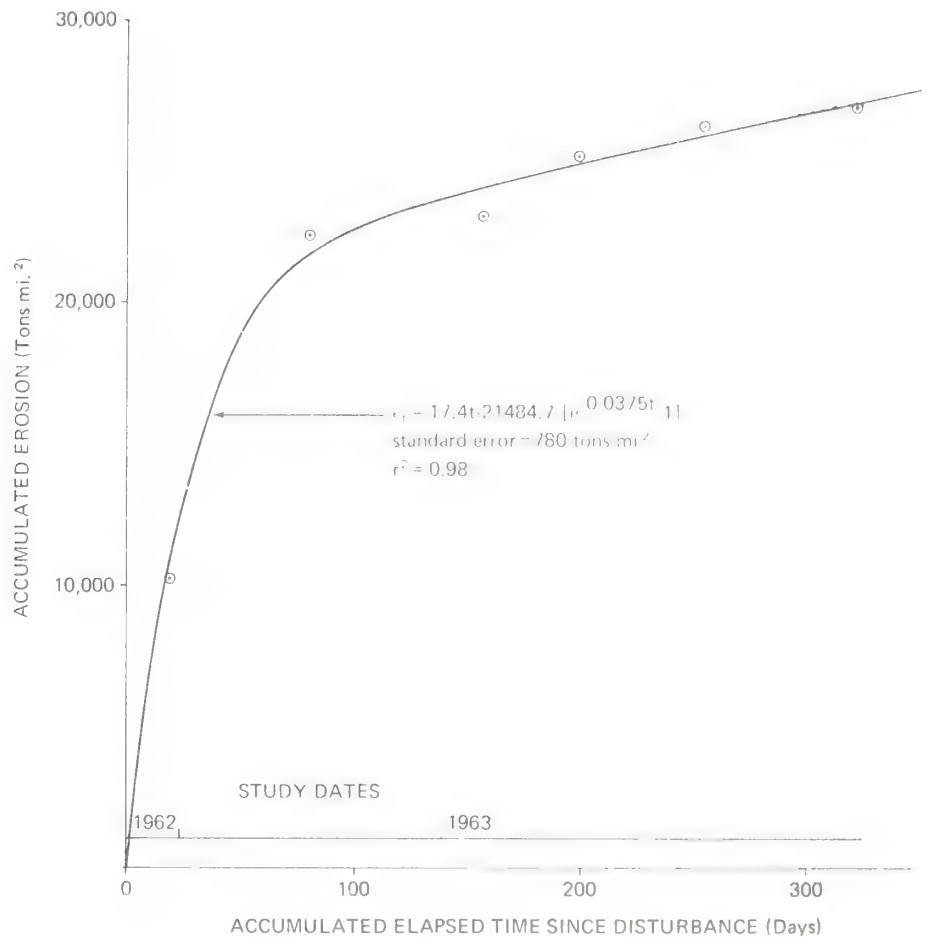
Road Fill Slope Erosion

Bogus Basin Study:--Other studies on granitic materials in the Idaho Batholith support the time-trend results reported above. These were designed to measure erosion rates on plots installed directly on steep road fills. One study was established in the fall of 1962 on the newly constructed Bogus Basin highway leading from Boise, Idaho, to the Bogus Basin Ski Resort (fig. 2). The study was designed to evaluate the effectiveness of various kinds of erosion-control measures and included a 1/100-acre unvegetated control plot that received no treatment. Erosion data were collected during the first year after construction: the first measurement was taken at 17 days and the last at 322 days (Bethlahmy and Kidd 1966).

Accumulated erosion data are summarized in figure 4. These data appear to fit the postulated erosion model; consequently, nonlinear regression was used to fit equation 9 to the data. The fitted regression model has a standard error of 780 tons mi⁻² day⁻¹ and an r^2 value of 0.98. All model parameters are significant at the 95 percent level of confidence.

Deadwood River Study:--Additional data (unpublished, USDA Forest Service, Intermountain Forest and Range Experiment Station, Forestry Sciences Laboratory, Boise, Idaho) are available to check the value for ϵ_n determined from the Bogus Basin data. These were collected on another road erosion study conducted on the Deadwood River drainage (fig. 2). The study was installed on the Deadwood road on a fill slope where site

Figure 4.--Accumulated erosion vs. time--Bogus Basin Study Area.



conditions were similar to those on the Bogus Basin road. Numerous attempts to revegetate this road fill by reseeding were unsuccessful because of harsh site conditions. Three unvegetated, 1/200-acre control plots were available on this study to compare to the Bogus Basin study. However, the Deadwood road fill was constructed in 1957; thus, the erosion data collected during the 1968-1972 sample period represent erosion rates expected from a 12- to 15-year-old unvegetated road fill. The average of these data should provide an approximate check on the ϵ_n value computed from the Bogus Basin data. The 3-year annual erosion average on the Deadwood plots is 9.1 tons mi⁻² day⁻¹ as compared to the ϵ_n value on the Bogus Basin plot of 17.2 tons mi⁻² day⁻¹. The lower value for the older study area could be caused by site differences, a tendency for erosion rates to continue to decrease beyond the time period used to fit the regression line, or both. In any case, considering the large variability usually associated with erosion data, the value for ϵ_n is again reasonable.

Role of Rainfall Energy and Vegetation

The derivation of the erosion model was based upon the assumptions that the erosive forces are constant over time and that no surface protection is available from vegetation and litter. Obviously, erosive forces are not constant over time in nature; consequently, the time trend in erosion may in fact be due to time trends in erosive forces.

Wischmeier and Smith (1958) showed that the erodibility index, defined as the kinetic energy of rainfall (foot-tons per acre-inch of rainfall) times the maximum 30-minute rainfall intensity (inches per hour) was a reliable index of the forces available for surface erosion. In addition, they developed a procedure for calculating the erodibility index that utilized rainfall-intensity data. An intensity rain gage was operated from early spring to late fall directly on the Deep Creek site for the entire study. During the remainder of the year, an intensity rain gage was operated at a similar elevation about 2 miles east of the Deep Creek study area.

The rainfall-intensity data were used to develop erodibility-index values for all storms occurring during the course of the Deep Creek study. No calculations were made when a snowpack existed because the erodibility index is irrelevant during such times. A degree-day procedure was developed for predicting the daily fluctuation of the snowpack at the study site. This procedure was based upon a detailed analysis of 6 years of snow-cover data collected monthly throughout the winter at eight sites in the vicinity of the study area. Wet adiabatic lapse rates were used to adjust the mean daily temperatures at the climatic station in the town of McCall, about 20 miles southwest of the study area, to those at the study site. Finally, a computer program was developed to predict daily snow accumulation and melt at the study site based upon daily precipitation and temperature.

The average erodibility index for each erosion-measurement period used in the study was computed by summing the erodibility indices for each rainstorm that occurred during snowless days and dividing by the number of days in the period. These data were then compared to the average rate of erosion for each measurement period (fig. 5).

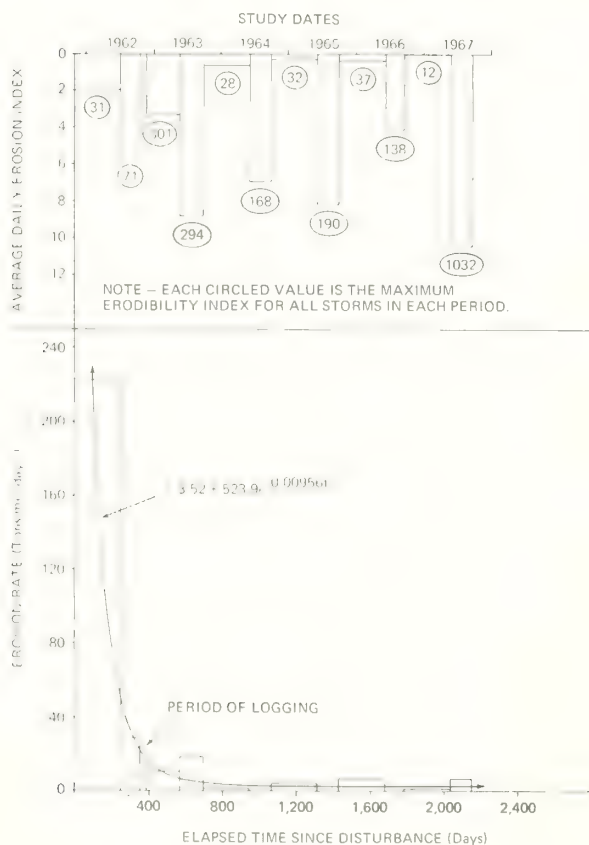


Figure 5.--Variations in erodibility indices and erosion over time--Deep Creek Study Area.

The instantaneous rate of soil erosion is also shown as a continuous curve on the figure. This rate was developed by differentiating the nonlinear regression fit of equation 9. Notice there is no time trend in the erodibility index similar to that shown for erosion in figure 5. The maximum erodibility index for all storms in each period is also shown on the figure; again no time trend is evident. These data suggest that variation in erosive forces did not have a primary influence on the time trend in erosion found on Deep Creek.

As one might expect, all vegetation within the area affected by road construction on Deep Creek was obliterated at the time of construction. Because of limited natural revegetation, the road remained essentially in this condition until after the study watersheds were logged a year later in 1962. At this time, standard postlogging erosion-control measures (water bars and grass seeding) were installed on the roads (fig. 5). Because of the time of year (November), no appreciable vegetation growth occurred until the following growing season: almost 2 years after construction. Notice in figure 3 that erosion had receded considerably by the end of the first year after construction, an indication that vegetation growth and installation of water bars was not the primary cause of the recession.

Unfortunately, no recording rain gage was operated at the Bogus Basin study area. However, climatic data are available from two nearby stations (Deer Point and Boise Airport) on each side of the study site. Data from these stations were adjusted to the elevation of the study site to develop erodibility indices for snowless days for each erosion-measurement period in the study (fig. 6). Snowless days were determined by using a procedure similar to that used on the Deep Creek study area. Note there is no time trend in either the average or the peak erodibility index that corresponds to the time trend found for erosion. Vegetation growth on the Bogus Basin plot was not a factor because essentially no vegetation growth occurred on the plot surface during the course of the study.

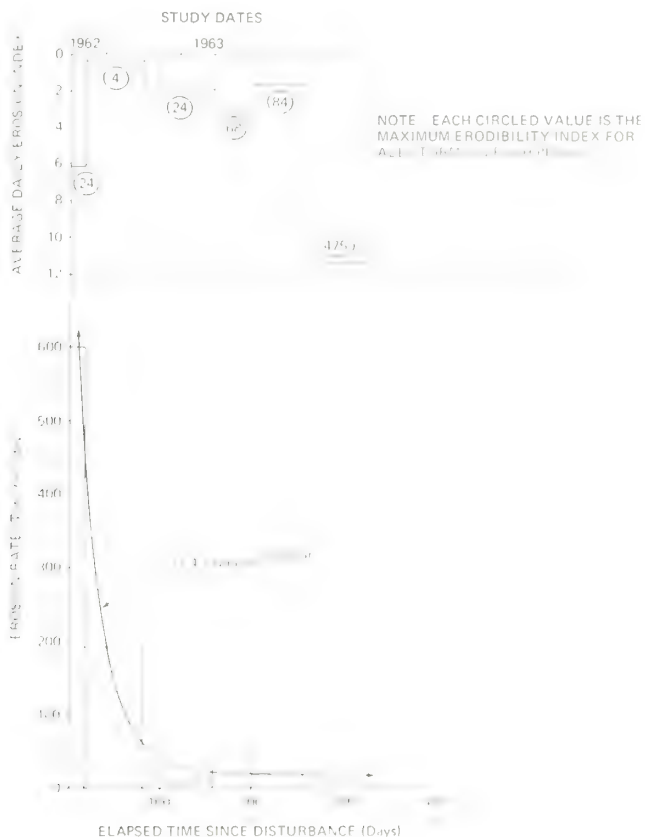


Figure 6.--Variations in erodibility indices and erosion over time--Bogus Basin Study Area.

DISCUSSION

Based upon experimental data on granitic materials from four different study sites, the derived exponential model for surface erosion over time appears to be appropriate. The model is useful to persons working in the area because it provides an estimate of the quantity and timing of surface erosion following disturbance. The need for such estimates is appreciated when surface erosion rates on disturbed lands are compared to those on undisturbed lands. Availability of a considerable body of sediment-yield data makes possible an estimate of the average erosion rate for undisturbed lands similar to the lands disturbed by road construction in these studies (Megahan 1972). The erosion rate for undisturbed lands averages about $0.07 \text{ ton mi}^{-2} \text{ day}^{-1}$. For the first year after disturbance, erosion rates per unit of area involved in road construction are three orders of magnitude greater than those on similar undisturbed lands; after almost 40 years, they are still one order of magnitude greater. The potential for damage by such accelerated erosion should be apparent.

Fortunately, accelerated erosion of this magnitude need not be accepted as an inevitable consequence of severe soil disturbance because it is possible to reduce the erosion with a variety of treatments. However, surface erosion follows an exponential relationship such that by far the largest percentage of soil loss occurs within 1 to 2 years after disturbance. Thus, erosion-control measures must be applied immediately after disturbance to be effective. A common approach is to reseed disturbed areas. However, seeding alone will have minimal effect because of slow initial growth responses; additional protection must be provided on the soil surface during the critical high-erosion period. Studies have shown that treatments such as mulching and transplanting on granitic road fills can reduce total soil losses dramatically. For example, Bethlahmy and Kidd (1966) reported that soil losses on the Bogus Basin study plots were not reduced at all by grass seeding alone, but were reduced about 70 and 98 percent when seeding was accompanied by mulching and mulch plus netting, respectively. Soil losses from erosion plots on the Deadwood road were reduced 98 percent by combining ponderosa pine planting with a straw mulch plus netting.

As with most studies where results are related solely to time, the true causes of the time trends are not identified. The studies reported here simply were not designed to evaluate the causes of time trends in erosion, but they were conducted in a manner that helps eliminate some likely causal factors. Obviously, variations in erosive forces will tend to modify erosion rates over time. However, these studies suggest that a widely used index of erosive forces (the erodibility index) was not well related to the time trends in erosion, at least during the initial period of rapid recession. Time trends in other erosive forces, such as wind or seepage flows, are a possibility, although no such effects were noted. Numerous studies attest to the ability of vegetation and mechanical measures to reduce erosion. Such treatment measures were applied late in Deep Creek and not at all on the road fill studies, which eliminates them as a cause of the rapid decrease in erosion. The foregoing suggests that variations in erosive forces (f) and protection (p) as defined in equation 1 did not cause the time trend. Therefore, it is postulated that the dominant causal factor was "armoring" of the erosion surface.

Wischmeier and others (1971) developed a procedure for estimating soil losses from farmland and construction sites based upon the universal soil-loss equation. No time trends in erosion were indicated by these studies. However, the study procedure and the fact that soil disturbance was not severe enough to include underlying parent material may have affected the results. Studies by other researchers suggest that time trends in erosion do occur under other soil and geologic conditions. Vice and others (1969) reported such trends following suburban highway construction in a 4.54-mi² drainage basin in Virginia. In this case, soil disturbance ultimately included about 11 percent of the study drainage. Anderson (1972) found decreasing time trends in sediment from poorly logged areas in California following severe flooding. Such areas contained logging roads next to channels and landings in draws. Sedimentation resulting from surface erosion on logging roads in Oregon decreased rapidly after an initial high rate following construction (Fredriksen 1970).

As is true of the Idaho studies reported here, the actual processes causing the erosion decreases with time were not evaluated. However, one additional study in West Virginia was more definitive; Reinhart and others (1963) found that sedimentation increases following logging resulted from erosion on skidroads. They observed the erosion process over time and reported:

The impact on water quality was greatest during and immediately after the logging operation.... Repeated disturbance during logging continually brought to the road surface a new supply of fine soil particles. Erosion decreased rapidly after logging, due first to the development on our soils of a partial erosion pavement (a surface cover of small stones) and later to vegetation growth on roads.

Obviously, the coefficients developed for the studies in Idaho will not apply elsewhere, but apparently the form of the basic time trend relationship is appropriate. It is important to note that the relationship applies only to surface erosion *following* disturbance: any additional disturbance will initiate a new surface erosion cycle. Furthermore, it applies only to *surface* erosion, not mass erosion.

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MEGAHAN, W. F.

1974. Erosion over time on severely disturbed granitic soils: a model. USDA For. Serv. Res. Pap. INT-156, 14 p., illus. (Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.)

A negative exponential equation containing three parameters was derived to describe time trends in surface erosion on severely disturbed soils. Data from four different studies of surface erosion on roads constructed from the granitic materials found in the Idaho Batholith were used to develop equation parameters. The evidence suggests that surface "armoring" was the dominant factor causing the time trends in surface erosion. The significance of time trends in surface erosion is discussed.

OXFORD: 116:116.3. KEYWORDS: surface erosion, vegetation, erosion energy, erodibility index, disturbed soil, soil erosion.

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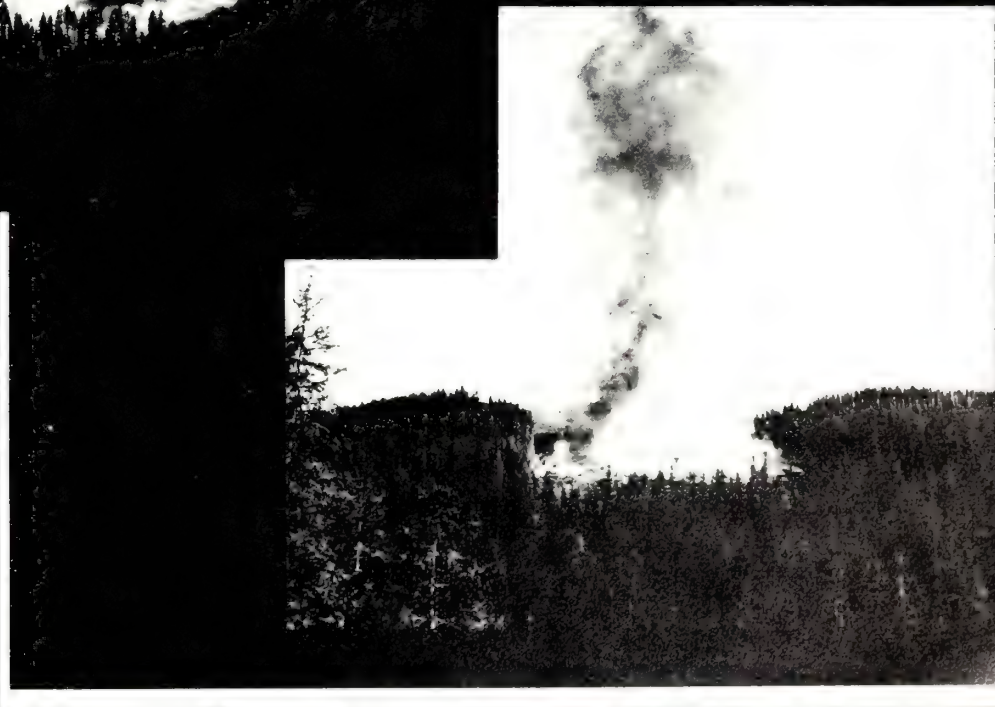
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SMOKE COLUMN HEIGHT RELATED TO FIRE INTENSITY



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SMOKE COLUMN HEIGHT RELATED TO FIRE INTENSITY

Rodney A. Norum

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Roger R. Bay, Director

THE AUTHOR

RODNEY A. NORUM is a research forester with the Fire Effects and Applications research workunit at Intermountain Station's Northern Forest Fire Laboratory, Missoula, Montana. He has a bachelor of science degree in electrical engineering from the University of Tennessee and a master of science degree from the University of Montana where he is currently working toward a doctorate in forest science. Rod is presently investigating the physical and biological effects of fire on various components of northern Rocky Mountain forest ecosystems.

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ABSTRACT

Height of slash fire smoke columns, commonly thought to be a function of atmospheric conditions alone, through a series of 10-acre experimental fires is shown to be strongly related to fire intensity. By conducting intense fires, land managers can possibly burn forest debris and still maintain air quality when atmospheric conditions are less than ideal for smoke dispersal.

OXFORD: 332.3: 436. KEYWORDS: slash disposal, fire use, atmospheric conditions.

INTRODUCTION

Disposing of logging debris grows increasingly difficult because of the constraints, demands, and restrictions being imposed on how it may be done. A growing public concern for air quality is one of the most important constraints on slash burning. Oftentimes land managers have given too little attention to proper smoke dispersal. The public, rightly so, will no longer tolerate degradation of the air. Land managers must assume the responsibility for burning slash in a way that maintains air quality.

Proper scheduling of fires in a given locality can avert the all too frequent occurrence of many fires, all burning at once, taxing the atmosphere's smoke dispersal capabilities. However, this alone does not relieve the need to conduct each fire to achieve the best possible smoke control.

The movement of smoke may be divided into two problem areas: (1) controlling the rise of smoke to its ultimate height, and (2) processes that disperse smoke at or near the maximum height. This paper addresses the problem of achieving good smoke elevation.

In the Northwest, prescribed burning is usually done in fall, when fuels are often quite moist and the atmosphere is frequently stable. Burning slash under such conditions results in low-intensity, smoky fires at a time when the atmosphere is least able to disperse the smoke.

Properly done, prescribed fires are aimed at specified objectives and for times and conditions most likely to achieve those objectives. This is true, not only for the purposes of hazard reduction and site preparation, but also for meeting the demands for acceptable elevation of the smoke.

Smoke that reaches a high altitude tends to stay at that altitude until completely dispersed. However, natural forces can also keep smoke near the ground if the fire and the atmosphere do not elevate the smoke initially. The result is then local, ground-level air pollution.

FACTORS AFFECTING SMOKE COLUMN HEIGHT

Because the vertical movement of smoke is dependent upon the temperature difference between the smoke and the surrounding air, much information on smoke movement has come from meteorological studies. The literature abounds with information on the influence of lapse rates on the rise and dispersal of smoke plumes. This is so universally true that, in the minds of many, characteristics of the heat source are of no consequence.

Does heat source influence smoke dispersal? Will a large, high-energy source produce a higher smoke column than a low-energy source under a given lapse rate or, in land managers' terms, will a hot slash fire give better smoke rise than a cool one? The answer to this basic question can have an important bearing on prescribed burning. If fire intensity does indeed influence smoke dispersal, the land manager may find himself less constrained by atmospheric conditions and with a greater flexibility to burn and still meet smoke management objectives.

FIRE INTENSITY

Fire intensity, the rate of heat released from a given fire, is commonly called the unit area energy release rate ($\text{Btu}/\text{ft}^2/\text{min}$). High fire intensity is achieved only through rapid consumption of large amounts of fuel. Rate of fuel consumption is mainly controlled by fuel moisture, but is also influenced by factors that affect rate of spread, such as wind velocity and steepness of slope. If fire intensity is an important factor in determining ultimate column height, variables that influence fire intensity should also be positively related to the height of smoke rise.

ATMOSPHERIC STABILITY

Atmospheric stability, the rate at which air temperature decreases with an increase in altitude above the surface of the earth, has some well-known effects of smoke rise. Unstable air rapidly decreases in temperature with an increase in altitude. Stable air decreases in temperature much less rapidly with an increase in altitude. *Very* stable air may even increase in temperature with an increase in altitude, resulting in the phenomenon called an inversion. Stable conditions tend to limit smoke rise and keep drift smoke near the ground. Unstable air, on the other hand, will assist smoke rise and help keep surface air clear. Mixing depth is a commonly used measure of atmospheric stability. Mixing depth is *not* always a good prediction of how high the smoke will go and should not be used or considered as such. The mixing depth is only an indication of boundary layer atmospheric stability.

METHODS

Recent experimental slash burning has yielded information that may help tie together some of the previous discussion. Forty-one instrumented fires, each 10 acres in size, were conducted by Flathead National Forest personnel for the Northern Forest Fire Laboratory over a period of 2 years.¹ The location was the Miller Creek Drainage on the Tally Lake Ranger District of the Flathead National Forest, Flathead County, Montana. The fires were broadcast burns of 10-acre beds of continuous slash created when a mature larch-fir stand was commercially clearcut. All residual stems were felled, and all slash was 1 or 2 years old when burned. Twenty-two of these fires were adequately documented to afford a data base for the study of smoke movement.

The actual maximum heights reached by the smoke columns were measured by an instrumented aircraft. Fuel quantity was measured before and after burning, and fuel moisture were sampled at fire time. Standard radiosonde ascents were performed immediately prior to the fires. All weather factors necessary for computing Fire Danger Rating System Indexes were measured and recorded on a regular basis. Watercan fire analogs (Beaufait 1966) were used to measure relative intensities between fires. A multiple regression analysis was used to identify variables which were related to ultimate smoke column heights. After some initial data reduction, the following variables were subjected to regression analysis:

Y(1) = column height (ft above m.s.l.)
 Y(2) = column height (ft above terrain)
 X(1) = mixing depth (ft above m.s.l.)
 X(2) = average upper duff moisture content (percent)
 X(3) = windspeed at fire time (20 ft above ground, mi/h) (5-min average)
 X(4) = watercan weight loss (g)
 X(5) = National Fire-Danger Rating Buildup Index
 X(8) = $1/X(2)$
 X(12) = potential heat yield of fuels in X(16) (Btu)
 X(13) = reaction intensity (I_R)
 X(14) = rate of spread (ROS)
 X(15) = weight of fuels; 0-1 cm diameter + 1-10 cm diameter + needles (g/m^2)
 X(16) = weight of fuels; 0-1 cm diameter + needles (g/m^2)
 X(17) = average fine fuel moisture; 0-1 cm + needles (percent)
 X(18) = $1/X(17)$
 X(19) = potential heat yield of fuels in X(15) (Btu)
 X(20) = mixing depth (ft above terrain)

A computer screen of all possible equations involving the above variables was performed along with machine plots of each independent variable against each dependent variable. The REX-Fortran 4 system for combinatorial screening of multivariate regressions as described by Grosenbaugh (1967) was used in the screening process. This initial attempt revealed that a linear function of X(1), X(12), X(16), and X(17) accounts for 63.2 percent of the variation experienced in Y(1). The computer plots of the variables indicated that variables X(3), X(5), and X(18) vary as some function of the column height above mean sea level. A computer program was employed to find the single-term equations of best fit for each of these three independent variables, versus column height. The resulting functions were added to the independent variable list. They are X(6), X(7), X(9), and X(11) below, and were selected as a convenience in curve fitting, not because of any physical inference. The independent variables found to be nonsignificant in the initial analysis were eliminated.

The final screen of all possible equations examined combinations of the following variables:

Y(1) = column height (ft above m.s.l.)
 Y(2) = column height (ft above terrain)
 X(1) = mixing depth (ft above m.s.l.)
 X(2) = average upper duff moisture content (percent)
 X(3) = windspeed at fire time (2- ft above ground, mi/h)
 X(4) = watercan weight loss (g)
 X(5) = National Fire-Danger Rating Buildup Index
 X(6) = square root of X(5)
 X(7) = $\log_{10} X(5)$
 X(8) = $1/X(2)$
 X(9) = square root of X(3)
 X(10) = square root of the potential heat yield of the (0-1 cm + needles) fuels
 X(11) = square root of X(8)

RESULTS OF THE ANALYSIS OF MILLER CREEK DATA

The six-variable regression equation with the smallest residual mean square had these six variables:

$X(1)$, $X(2)$, $X(3)$, $X(4)$, $X(9)$, $X(11)$

where

$X(1)$ = mixing depth (ft above m.s.l.)
 $X(2)$ = upper duff moisture content (percent)
 $X(3)$ = windspeed (20 ft above ground, mi/h)
 $X(4)$ = watercan weight loss (g)
 $X(9)$ = square root of $X(3)$
 $X(11)$ = square root of $1/X(2)$

The R^2 (coefficient of multiple determination) for this regression is 0.80. That is, 80 percent of the variation in the column height is explained by the regression.

Source of variation	df	SS	MS	F
Due to regression	6	84,308,688	14,051,448	9.958**
Error	15	21,165,840	1,411,056	
Total	21	105,474,520		

Since tabular $F_{0.01}$ with 6 and 15 degrees of freedom is 3.94, $F_{6/15 \text{ df}} = 9.958$ is significant at the 0.01 level. Standard error of the estimation = 1,188 ft.

A "t" test of the regression coefficients to determine if the coefficients are significantly different than 0.0 yielded the following results:

Coefficient	"t"	Level of significance
$b(1)$	1.789	0.10
$b(2)$	1.557	.20
$b(3)$	3.66	.01
$b(4)$	2.385	.02
$b(9)$	3.741	.01
$b(11)$	1.224	.30

From this test one must conclude that the ultimate column height and fire intensity (watercan weight loss) are closely related. By the same token, the mixing depth is only loosely related to the column height.

As a further verification of this conclusion, a regression analysis was performed using only fuel and weather variables. One simple equation resulting from the analysis is:

$$Y = f \ X(1), X(3), X(7), X(9)$$

where:

X(1) = mixing depth (ft above m.s.l.)
 X(3) = 5 minute average windspeed, 20 ft (mi/h)
 X(7) = Log₁₀ (BUI)
 X(9) = square root X(3)

The actual regression equation is:

$$Y(1) = -5,578.3 + 0.0381 X(1) - 2,183.6 X(3) + 3,683.9 X(7) + 10,634.0 X(9)$$

<i>Source of variation</i>	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>
Due to regression	4	79,334,496	19,833,624	12.899**
Error	17	26,140,032	1,537,649	
Total	21	105,474,528		

Since tabular F distribution with d = 0.01, and df = 4 and 17 is 4.34, the regression is significant at the 0.01 level. The standard error of the estimation is 1,240.0 ft. The coefficient of multiple determination is:

$$R^2 = \frac{\text{Regression SS}}{\text{Total SS}} = \frac{79,334,496}{105,474,540} = 0.752$$

A "t" test of the regression coefficients yields the following:

<i>Coefficient</i>	<i>"t"</i>	<i>Level of significance (df = 17)</i>
b(1)	1.759	0.10
b(3)	4.670	.001
b(7)	2.558	.05
b(9)	5.020	.001

This test indicates that only b(1) is of questionable significance. There exists a probability of 10 percent that assuming b(1) is not zero would lead to an erroneous association.

Again those variables influencing fire intensity (wind and fuel dryness) are notably more closely related to the ultimate level of smoke rise than was the mixing depth.

CONCLUSIONS

Atmospheric stability, expressed as mixing depth, is shown to be eminently inadequate for describing the ultimate level of smoke rise from high-intensity, 10-acre broadcast slash fires. The level to which smoke rose on 22 of these fires is shown conclusively to be closely related to the character of the fire, namely fire intensity.

Management Interpretation

Land managers burning slash must prepare environmental impact statements and burn to maintain a quality air resource. Many fire managers believe that low-level atmospheric stability, expressed as mixing depth, is an absolute prediction of how high the smoke will go. The findings expressed in this paper show that in high-intensity broadcast slash fires of 10-acre, size, the characteristics of the fire are overwhelmingly important to the elevation of the smoke.

Although low-intensity fires do tend to produce a column height more nearly equal to the mixing depth, some of the intense fires used in this study produced smoke columns 8,000 ft higher than the mixing depth. This is significant to the land manager who must accomplish a certain amount of burning in a limited amount of time while assuring good smoke dispersal. A brisk, hot fire can overcome a shallow stable layer of air and produce a high smoke column; however, it would be irresponsible to set off a wet, cool, slow-moving fire under similar lapse rates.

Ideal conditions for good elevation of the smoke are a high mixing depth and fuels dry enough to produce an intense fire.

Nevertheless, the results of this study indicate that a manager should not necessarily refrain from burning solely because the atmosphere is more stable than desirable, if he conducts intense fires. Intense fires are compatible with other management objectives such as seedbed preparation and hazard reduction as well.

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Site productivity classification for selected species on winter big game ranges of Utah

Richard Stevens
A. Perry Plummer
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EXPERIMENT STATION
Ogden, Utah 84401



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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U. S. Department of Agriculture
Ogden, Utah 84401
Roger R. Bay, Director

AUTHORS

RICHARD STEVENS is a Game Biologist for the Utah Division of Wildlife Resources. He received his B.S. degree in Range Management (1965) from Brigham Young University, and his M.S. degree in Range Management (1968) from the University of Arizona. From 1968 to 1969 he was a Range Conservationist with the USDA Forest Service. He has been in his present position since 1969.

A. PERRY PLUMMER is a Range Scientist for the Intermountain Station at Ephraim. He has worked in range research for the Station since 1936. He received his B.S. degree (1935) and his M.S. degree (1939) in Botany from the University of Utah. His research has been principally concerned with the restoration of western ranges.

CHESTER E. JENSEN is Principal Statistician for the Intermountain Forest and Range Experiment Station. Previously, he held the same position at the Northeastern and Central States Forest Experiment Stations. Mr. Jensen, who holds a master of forestry degree from Michigan State University, received his training in graduate statistics at Iowa State University.

BRUCE C. GIUNTA is a Game Biologist for the Utah Division of Wildlife Resources. He received his B.S. degree in Wildlife Management (1963) and his M.S. degree in Wildlife Biology (1968) from Colorado State University. Previous to his assignment in Ephraim in 1971, he was superintendent of the Hardware Game Management Unit east of Hyrum, Utah.

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ABSTRACT

Prospective range restoration areas must be judged capable of satisfactory response before restoration is attempted. Both underestimation and overestimation of site potential for such areas have created serious problems for land managers in the juniper-pinyon and sagebrush-grass types.

Reported here are the results of a 5-year study to develop an objective and more reliable system for evaluating site potential.

Productivity of big sagebrush, black sagebrush, and a grass mixture was correlated at 21 representative sites with edaphic, topographic, and climate conditions that significantly affect production. The analysis provided mathematical models from which charts for each plant species group have been developed. A proposed treatment site can be classified broadly for productivity potential. The potential is charted for a range of values of the measurable variables (soil properties, precipitation, percent slope, etc.) that were found to be most strongly associated with production.

INTRODUCTION

Most of the winter big game ranges and a large portion of the winter livestock ranges of Utah are in the juniper-pinyon and sagebrush-grass types. Although approximately 40 percent of Utah, or 20 million acres, is occupied by these two types (Valentine 1961; Isaacson¹), more than three-fourths of this acreage is severely depleted of the grasses, forbs, and shrubs necessary to big game survival. The condition of these lands greatly reduces their value to livestock, and water and soil losses are high (Plummer and others 1968) (fig. 1). The importance of these two range types can hardly be overemphasized because they are needed to provide the winter forage base for deer and elk and grazing area for livestock in the spring and fall.

In an effort to improve depleted winter ranges in Utah, more than 200,000 acres in the juniper-pinyon type have been chained and seeded to mixtures of grasses, forbs, and shrubs (fig. 2). Although seeding has been successful on most of this land, stand establishment on some projects has been mediocre or poor. This study was undertaken to improve our ability to evaluate productivity potential of a prospective restoration site. In the past, such evaluation has occasionally been based on soil surveys, but for the most part it has been subjective, based on the personal experience of the individual land manager. The rising cost of improvement projects and the extensive acreage yet unimproved emphasizes the need for reliable criteria for site productivity potential to guide restoration projects.

Little information is available on the productivity potential of the juniper-pinyon and sagebrush-grass communities. Site index research on coniferous and deciduous forests has little application to artificial restoration in juniper-pinyon and sagebrush-grass communities.

¹H. E. Isaacson. Ecological provinces within the pinyon-juniper type of the Great Basin and Colorado Plateau. Unpubl. M.S. thesis, Utah State Univ., Logan, 44 p., 1967.



Figure 1.--Juniper-pinyon site where understory has been severely depleted.



Figure 2.--Deer on improved winter range. The juniper-pinyon site has been improved by double chaining and seeding of a mixture of grass, forbs, and shrubs.

Work closely related to site index research, however, has been done by Gates and others (1956) and by Fosberg and Hironaka (1964), who report the significant effect of selected soil properties on the distribution of plants in Utah and Idaho. Yield and composition tables have been compiled for most range sites in Utah, and these have been correlated with precipitation and soil (Mason 1971). Medin (1960), working with mountain mahogany (*Cercocarpus montanus*), also found that soil and topographic characteristics affect annual production. Davis² reported from Nevada that some soil properties, along with precipitation, are useful in estimating production on a salt desert range.

Research has shown how variations in precipitation affect herbage production of certain grass and shrub species in the sagebrush-grass and juniper-pinyon communities (Cooper and Hyder 1958; Passey and others 1964; Blaisdell 1958; and Clary 1971). Hutchings and Stewart (1953) discovered that precipitation is the most important influence on production of a number of shrubs and grasses in the salt desert shrub type. Currie and Peterson (1966), working in Colorado, found that growing-season precipitation could be used to predict yields of established standard crested wheatgrass (*Agropyron desertorum*).

This study seeks to identify edaphic, topographic, and precipitation variables that significantly influence annual production on winter game range in Utah, and to find ways to use these variables to predict productivity potential of a given site. The study included big sagebrush, black sagebrush, a mixture of perennial grasses, winter rye, and German iris on 21 sites. The winter range studied is used from late fall through early spring. Regression analysis of the resulting data resulted in the development of three prediction models and finally, in productivity-potential charts for easy application by users.

²J. Barry Davis. Estimating plant production from soil and floristic correlates in Hot Creek Valley, Nevada. Unpubl. M.S. thesis, Univ. Nevada, Reno, Renewable Natural Resources, 58 p., 1971.

STUDY AREA

Twenty-one study sites, which we believe to be representative of Utah's principal big game winter ranges, were selected in central Utah. Thirteen are located within juniper-pinyon communities, two on ecotones between the mountain brush and juniper-pinyon types, three in sagebrush-grass communities (fig. 3), two on abandoned dry farms formerly occupied by juniper and sagebrush (fig. 4), and one within a shadscale-sagebrush community. Slopes vary from 0 to 41 percent and exposures are primarily west and south. Soil pH ranges from 7 to 8.9. A calcium carbonate layer is present on most sites, but only on the shadscale-sagebrush area is there a cemented hardpan. Annual precipitation varies from 5 to 25 inches.

Soils of the 21 sites are derived from eight geologic formations. From oldest to youngest they are (1) Lower Oquirrh formation--mostly quartzite with some shale, (2) Upper Oquirrh formation--mostly limestone with some shale, (3) Arapien formation--calcareous shale with sandstone and shale, (4) North Horn formation--sandstone and shale, (5) Flagstaff formation--limestone with some calcareous shale, (6) Colton formation--hematitic, calcareous shale with some sandstone and conglomerate, (7) Green River formation--limestone with some calcareous shale, and (8) extrusive volcanics--mostly porphyritic Andesite (personal communication, Frederic C. Lohrengel II, 1972).



Figure 3.--Study site within a sagebrush-grass community 2 years after plot establishment. The production potential for this area was found to be below average for big sagebrush, black sagebrush, and the grass mixture.



Figure 4.--Study site on abandoned dry farm 2 years after establishment. The potential production of this site was found to be above average for black sagebrush and average for big sagebrush and the grass mixture.

METHODS

Species and Plot Design

A number of plant species having different growth requirements were selected to measure productivity. Big sagebrush (*Artemisia tridentata*) and black sagebrush (*A. nova*) are fast-growing, palatable shrubs, well-adapted to winter big game ranges in Utah. Fairway crested wheatgrass (*Agropyron cristatum*), intermediate wheatgrass (*A. intermedium*), Russian wildrye (*Elymus junceus*), and southern smooth brome (*Bromus inermis*) have a wide range of adaptability and have been successful on many seeding projects. These grasses were planted as a mixture. Because the shrub and grass species selected may require different conditions for maximum production, it was not expected that an optimum site for one species would necessarily be an optimum site for all.

Two other species were planted to determine if their production on a given site could be used as an index to potential productivity for the above-named sagebrush and grass species. They were annual winter rye (*Secale cereale*) and German iris (*Iris germanica*). Both have a wide range of adaptability.

At each site, 2-year-old seedlings of big sagebrush, black sagebrush, and iris rhizomes were planted in April 1964. Transplants of each species were obtained from the same populations to reduce ecotypic variations within a species. The perennial grass mixture and winter rye were sown in November 1964. Winter rye was also sown in the fall of 1965 and 1966. All plantings and seedings were arranged in twice-replicated, randomized blocks (fig. 4). Each block of big sagebrush, black sagebrush, and iris contained five 15-foot rows with six plants per row. The rows were on 30-inch centers. Blocks for the grass mixture and winter rye consisted of eleven 6½-foot rows each with 15-inch centers. The grass mixture (comprised of equal weights of each species) and winter rye were sown at the rate of 10 and 40 pounds per acre respectively.

Border rows in each species were used as isolation strips between species plots. Responses from these plants were not included in the data analysis. Plants other than the test species were periodically weeded out to eliminate outside competition as a complicating factor. Livestock was excluded from each study site.

Measurements

When plots were established, percent slope and exposure azimuth were measured at each site.

Soil examinations at each site were made in accordance with standard Soil Conservation Service soil survey methods (USDA Soil Survey Staff 1951). Soil profile pits were dug and total depth in inches of each recognizable horizon was measured. For each horizon, mottling, color, texture, structure, consistency, and percent coarse fragments (greater than 3/4-inch diameter) hereinafter referred to as percent rock, by volume were recorded. Soil samples for each horizon were collected and analyses were made for percent soil organic matter, pH, percent calcium carbonate, percent nitrogen, available phosphorus pentoxide (P_2O_5) in pounds per acre, available potassium in parts per million, cation exchange capacity, expressed on a percent-by-weight basis for the less-than-2-mm fraction, and moisture-holding capacity at 1/3 and 15 atmospheres.

Precipitation was measured at or near each site for the duration of the study with standard 8-inch precipitation gages.

Herbage production was the variable measured as a predictor. Initially, total herbage production, height, and crown spread measurements were considered to be the variables most likely to have predictive value. Preliminary analysis showed, however, that production was a much better expression of plant response than either height or crown spread, and consequently, these two variables were eliminated. The weight estimate method described by Pechanec and Pickford (1937) was used to determine field green-weight production. Green weights were later converted to air-dry weights for analysis.

Herbage production of winter rye was measured annually from 1965 to 1967. Production measurements on the other species were not made until the plants were near maturity in 1967. Production was measured again in 1968 and 1970. In the latter part of June 1968, one of the most severe June frosts on record occurred, preventing normal development of seed heads in the big and black sagebrush. Grass forage, which was almost completely frozen, had little regrowth, and there was no seed head development after the frost. The reduced and erratic production measurements for 1968 were not included in the data analysis.

Data Analysis

The analysis of the data gathered in the study was aimed at isolating the environmental variables that could best serve as production predictors. Plot soil characteristics, slope, exposure, and precipitation, in all combinations, were screened as independent variables in linear additive regression models, for strength of relation to corresponding 1967 and 1970 dry-weight production estimates. Those variables contributing most strongly to R^2 (that is, explaining the greatest amount of variance in production) and having direction of effect in accord with biological expectation were identified. For these variables, a more sensitive interaction model was subsequently developed as explained in the Appendix. This process, in its entirety, was applied to the data for big and black sagebrush and the grass mixture.

The three final models formed the basis for the productivity charts presented. Future data accumulated in field use may permit improvement in the predictive accuracy of the interim formulas and charts developed.

Note that neither iris nor rye proved suitable as productivity indicators. Iris had suffered extensive fungal damage and rye production was unaccountably variable.

RESULTS

Perennial Grass Mixture

For the grass mixture, the variables most strongly associated with production were those related to available soil moisture during the growing season. They included annual water-year precipitation, May precipitation, percent rock in the subsoil, and percent slope. The model that included these variables produced a coefficient of determination (R^2) of 0.76. In general, the production responses were in accord with biological expectations.

Expectations.--In semiarid areas, precipitation limits production. With increases in either May or annual precipitation, the curve of expected production is sigmoid (S-shaped). Because May is generally the period of maximum growth in the areas under consideration, precipitation received during this period can be of critical importance. At the extreme of no precipitation in May and no residual soil moisture from winter or early spring precipitation, there would be little or no production because soil moisture would be below the wilting point for grasses. As precipitation increased to the point where soil moisture was available, production could be expected to increase until added increments of precipitation could not be effectively utilized by the plants, and the production curve would tend to level off. The same expectation would presumably hold between extremes of annual precipitation; high annual precipitation does not occur in this area, however.

Grass production was expected to diminish sigmoidally with increased rockiness in the subsoil, which reduces the water-holding capacity of the profile. The fact that the grasses have shallow fibrous root systems and were planted in soils with very shallow A horizons would tend to accentuate this effect.

The relation of the amount of moisture entering the soil to the amount of precipitation depends, at least in part, on the slope of the area. At zero slope, the infiltration of moisture, the resulting soil moisture level, and grass production are expected to be near a maximum. With increased slope, overland flow and erosion increase and infiltration decreases, reducing soil moisture storage and grass production. The expectation was for a sigmoidal decrease between extremes of slope.

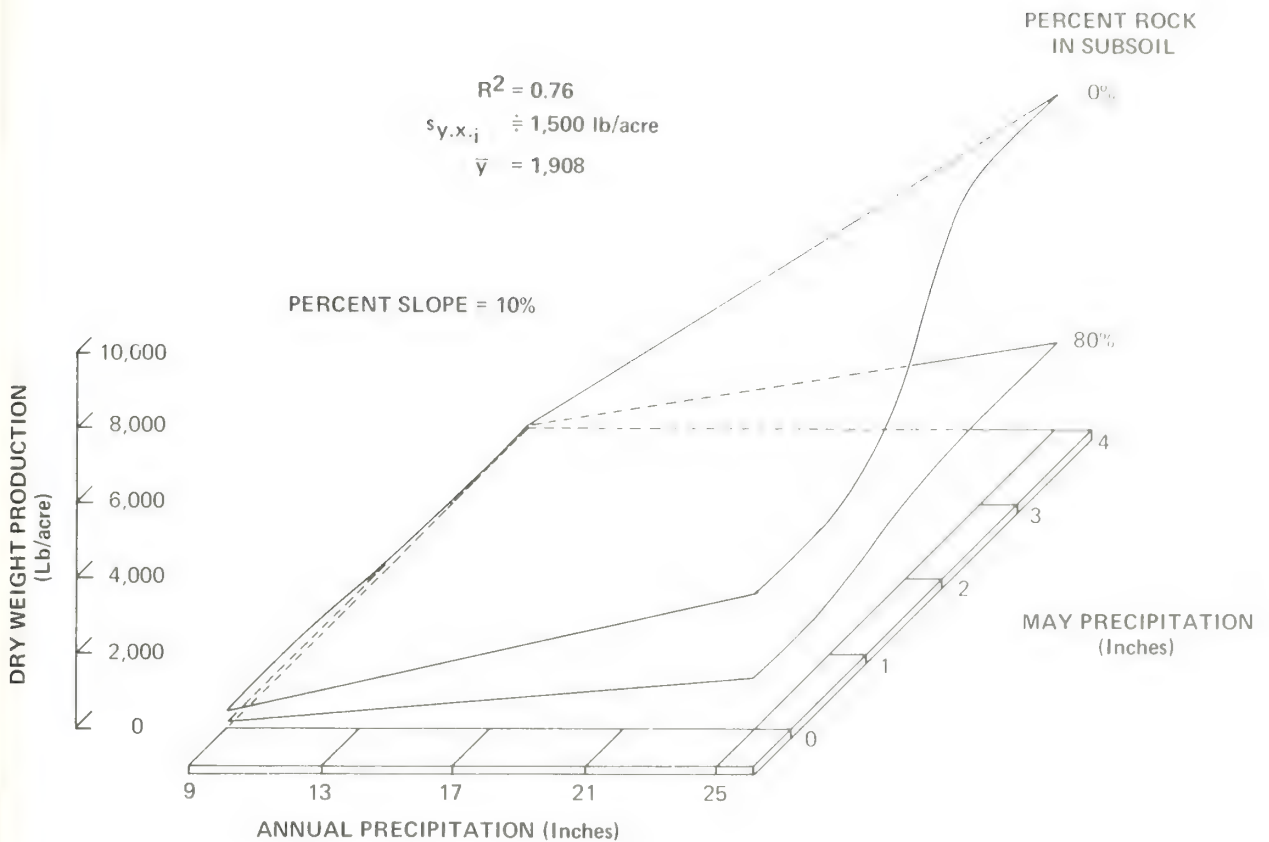


Figure 5.--Graphic illustration of the effect of four variables (annual precipitation, May precipitation, and percent rock in the subsoil at three levels all at an average slope of 10 percent) on the production of a grass mixture.

Results.--During the course of the study, May precipitation ranged from 0.1 to 3.3 inches; as May is the period of greatest growth of all species in the grass mixture, it was not surprising that May precipitation exerted a full, strong sigmoidal effect on production, the greatest increase occurring between 1 and 3 inches of precipitation.

For annual precipitation, percent rock, and percent slope, the expected production response was fundamentally realized, but only linear portions of the expected sigmoidal effects could be identified in the analysis. Perhaps this incomplete response was due to the limited range in annual precipitation (5 to 25 inches) and percent slope (0 to 21 percent, only one site exceeding 21 percent) on the study areas. Percent rock, however, ranged broadly (0 - 80 percent), and the expected negative relation to production was evident.

It was possible to identify the interaction between precipitation variables and percent rock, and this was incorporated in the final prediction model. After interaction was fitted, slope was fitted as an additive effect. The magnitude of effects in the three-way interaction can be seen in figure 5. Note that the change between surfaces at 0 and 80 percent rock is a linear function of percent rock. The linear effect of slope (not shown) is small.

Big Sagebrush

The components of the production model for big sagebrush were found to be annual precipitation and depth of the soil horizons A through C¹ ($R^2 = 0.56$). May precipitation had no discernible effect on production. Apparently big sagebrush, a relatively

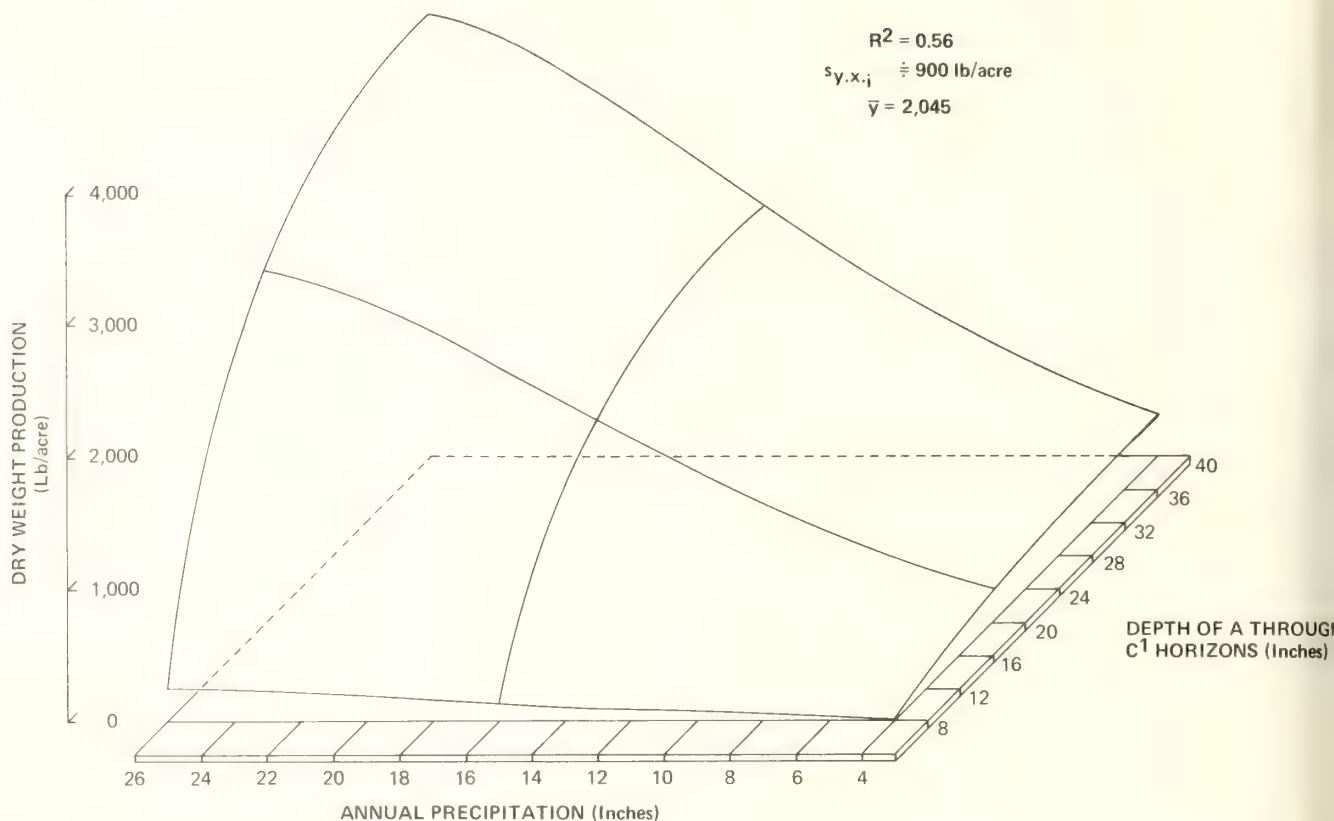


Figure 6.--Graphic illustration of the effect of annual precipitation and depth of horizons A through C¹ on the production of big sagebrush.

deep-rooted species, is not very sensitive to moisture fluctuations in the surface horizons that result from either a wet or dry May. Most of the annual growth of this species is probably dependent on deep soil water reserves.

The expected sigmoidal effect of annual precipitation on production was not evident over the relatively limited range of annual precipitation (5 to 25 inches). The data revealed a production trend that was basically linear.

The appearance of depth of horizons A through C¹ as a model component again seems reasonable--this depth would be a critical factor in root development and available moisture-holding capacity for a deep-rooted species. With no soil depth, production should be zero, but it could be expected to increase with greater depth of horizons A through C¹ up to a point of diminishing return, that is, one at which added depth would not be wetted even in the highest precipitation areas included in the study. Extremes of depth of horizons A through C¹ occurred on the study sites, and the expected sigmoidal effect on production was readily apparent from the data.

Production tended to level off when depth of the C¹ horizon was more than 34 inches. The soil types on the sites and the amount of precipitation in normal years suggest that any water percolating deeper than 34 inches is probably not available for long periods. Consequently, a C¹ horizon deeper than 34 inches without moisture would not be expected to greatly increase production. The magnitude of the final interacting effect of two variables on production for big sagebrush is shown in figure 6.



Figure 7.--Three-year-old plants of black sagebrush and big sagebrush, showing the more fibrous root system of black sage and the deep taproot of big sage.

Black Sagebrush

The model for this species included annual precipitation, percent rock in the subsoil, and depth to the point of rapid increase in concentration of calcium carbonate ($R^2 = 0.65$).

This species typically has a more shallow fibrous root system than big sagebrush (fig. 7). Consequently, the species is more responsive than big sagebrush to variables associated with moisture near the soil surface. Therefore, it was thought that May precipitation should show as a significant variable in production of black sagebrush as it did for the grasses. As for big sagebrush, however, only a linear annual precipitation effect could be identified in the data. Perhaps this incomplete response could be attributed to the limited range in precipitation.

Black sagebrush has been observed to grow most often in rocky to semirocky, well-drained soils, leading to the assumption that small amounts of rock in the subsoil may not be detrimental to production. The expected sigmoidal effect of percent rock on production was evident, however. No doubt as rock percent reaches a given level, moisture storage capacity does become limiting and results in reduced herbage production. Although there was relatively little production loss between 0 and 20 percent rock, production declined to near 0 when rock content neared 80 percent.

Forage production is usually low on soils with shallow calcium carbonate layers. Under certain conditions, depth to the carbonate layer is a fairly reliable index to

the average annual precipitation. Such conditions as position of the contrasting soil layers and presence of and rates of deposition and erosion complicate evaluation of the influence of the calcium carbonate layer in relation to the other variables. As this layer appears at greater depths, the available moisture, aeration, and potential rooting area may also be greater, depending on the thickness of the layer and the amount of cementing which has taken place. The broad range of this variable in the data (0 to 50+ inches) enhanced the strong sigmoidal effect that was evident. Virtually all the change attributable to depth of the calcium carbonate layer occurred in the range of 0 to 12 inches. Black sage production was finally expressed as a function of the three-way interaction of these variables as shown in figure 8.

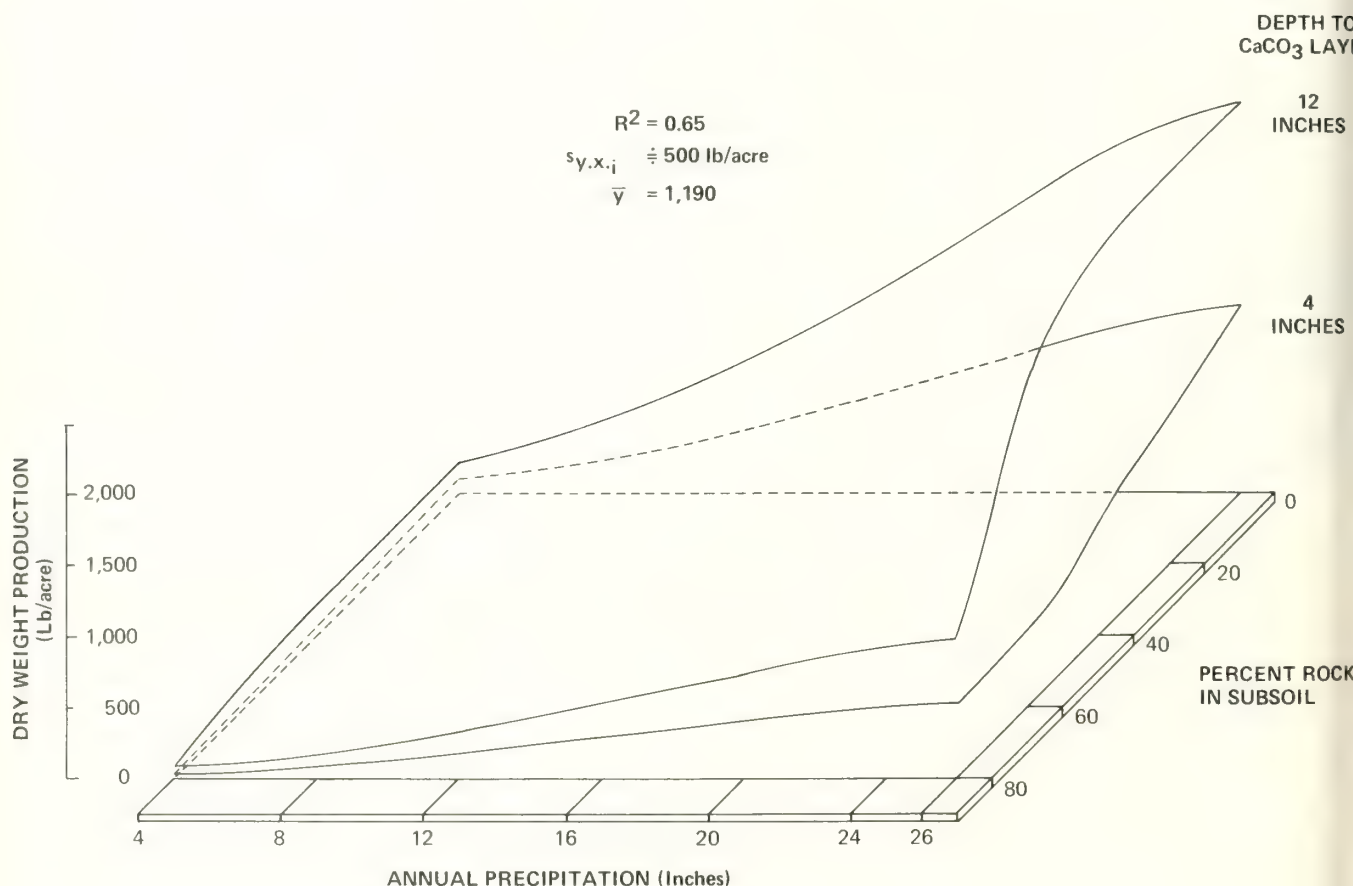


Figure 8.--Graphic illustration of the effect annual precipitation, percent rock in the subsoil, and three depths to a calcium carbonate layer have on the production of black sagebrush.

PRODUCTIVITY-POTENTIAL CHARTS

The derivation of estimating equations for each plant species group from the initial production model is described in the Appendix. The equations were used as the basis for computerized production estimates for pertinent levels of the variables in each model. The estimates for each species group were then divided into five productivity-potential groups: (1) low; (2) below average; (3) average; (4) above average; and (5) high. The predicted range in production (pounds per acre) of the five productivity groups under mature, full, pure stand conditions are given in table 1.

Table 1.--*Productivity-potential groups and their predicted range of production under mature, full, pure stand conditions for each species*

Productivity groups	Predicted range of production		
	Grass mixture	Big sagebrush	Black sagebrush
----- Air-dry lb/acre -----			
1. Low	0 - 299	0 - 199	0 - 199
2. Below average	300 - 1,199	200 - 699	200 - 599
3. Average	1,200 - 2,999	700 - 1,499	600 - 1,399
4. Above average	3,000 - 4,499	1,500 - 2,199	1,400 - 1,999
5. High	4,500 -	2,200 -	2,000 -

We do not expect that pure, full stands over an entire area will be achieved or are even desirable for any one species under most range conditions. We judge the use of specific production estimates rather than broad productivity groups to be unwise because of sampling and measurement constraints in the basic data. Actual production will vary from that predicted by reason of factors not accounted for in these models, such as quality and quantity of seed, adaptability of species, methods used in site preparation and seeding, time of seeding, moisture and temperature conditions during establishment period, and season and degree of use.

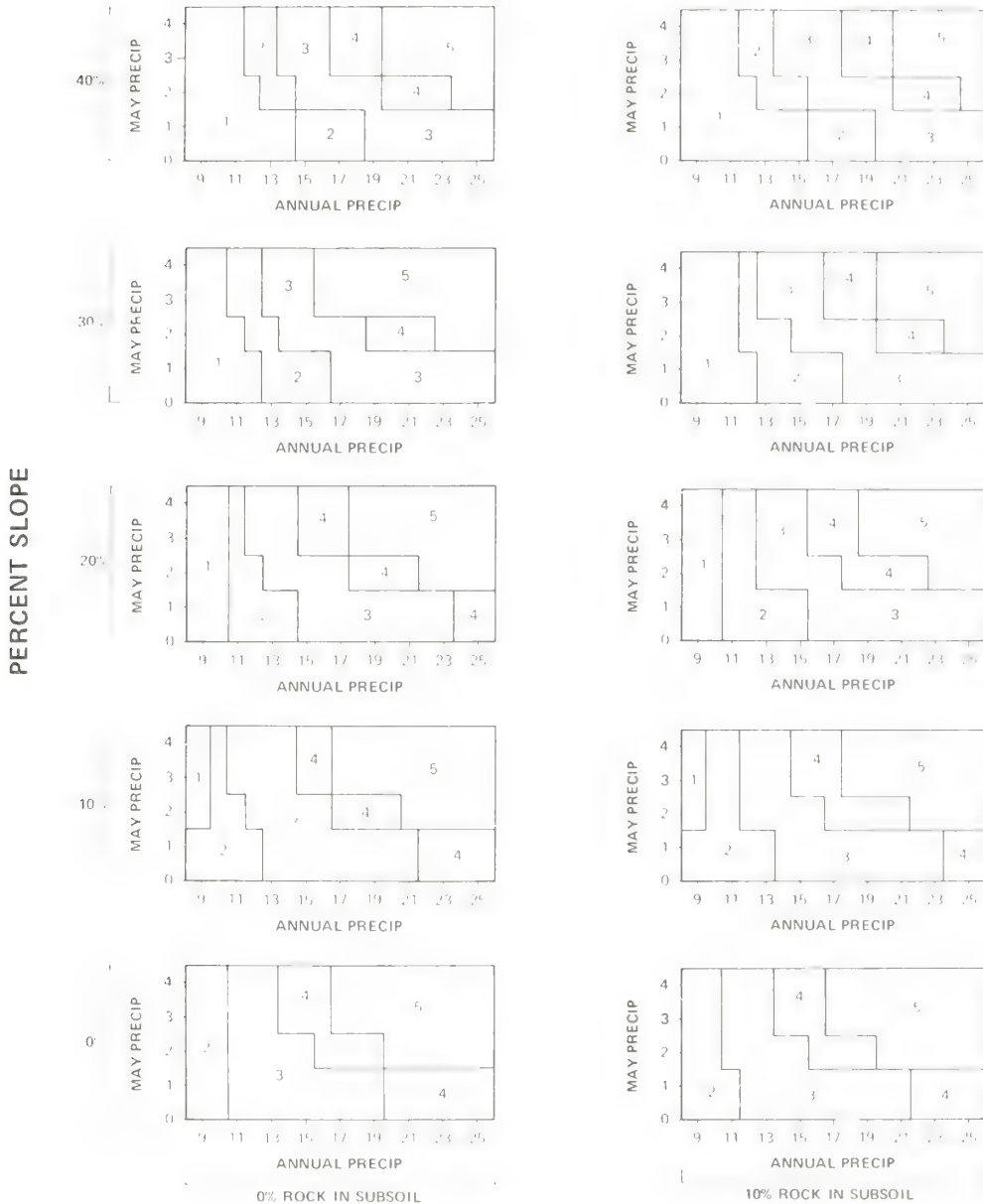
The productivity-potential tables for the three species are given in figures 9, 10, 11, 12, and 13. With these charts, proposed treatment sites may be classified according to productivity group. Where a grass mixture is to be planted, the average water-year precipitation, average May precipitation, percent slope, and percent rock (larger than 3/4 inch) in the subsoil should be determined. For big sagebrush, information is needed on average water-year precipitation and depth of the A through C¹ horizons. Where black sagebrush is to be seeded, knowledge of average water-year precipitation is required along with percent rock (larger than 3/4 inch) in the subsoil, and if applicable, the depth to the point (if present) of rapid increase in concentration of calcium carbonate. Where such a point is not present, a figure of 40 inches may be used. A concentration of calcium carbonate at this depth and deeper has no significant effect on production and is therefore the greatest depth indicated in the charts. When the appropriate information is obtained for a given area, the productivity classification of that area can be readily obtained by applying the data to the appropriate chart in figures 9, 10, 11, 12 and 13 as illustrated in table 2.

The guides outlined herein should be applicable throughout most of the range of juniper-pinyon and sagebrush-grass types.

Table 2.--*Example of data required and charts used to determine productivity-potential classification groups for each species for a specific site*

Species	Variables required	Measurements from site	Productivity classification group for site
Grass mixture	Percent rock in subsoil Percent slope Annual water-year precipitation (Oct. 1-Sept. 30) May precipitation	20 10 16.2 in. 1.8 in.	Group 3 (average) from figure 10
Big sagebrush	Annual water-year precipitation (Oct. 1-Sept. 30) Depth of soil horizons A through C ¹	16.2 in. 27.0 in.	Group 4 (above average) from figure 12
Black sagebrush	Percent rock in subsoil Annual water-year precipitation (Oct. 1-Sept. 30) Depth to CaCO ₃ layer	20 16.2 in. 31.0 in.	Group 4 (above average) from figure 13

GRASS MIXTURES I



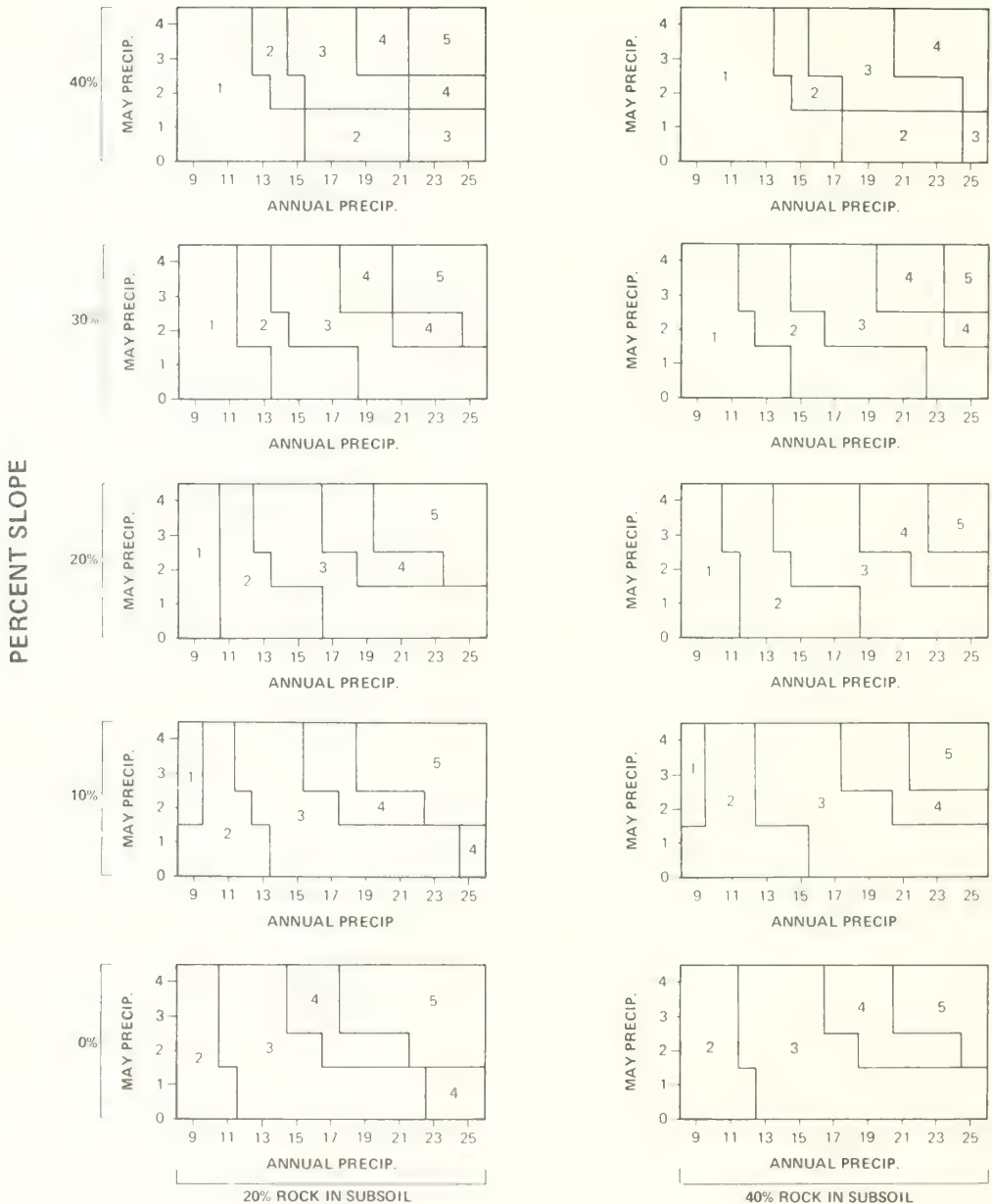
LEGEND

PRODUCTIVITY – POTENTIAL GROUPS

- | | | |
|------------------|------------------|---------|
| 1. LOW | 3. AVERAGE | 5. HIGH |
| 2. BELOW AVERAGE | 4. ABOVE AVERAGE | |

Figure 9.--Chart for determining site productivity-potential group for grass mixtures according to level of annual water-year precipitation (inches), May precipitation (inches), percent rock in the subsoil (volume; coarse fragment greater than three-fourths inch), and percent slope of area.

GRASS MIXTURES II



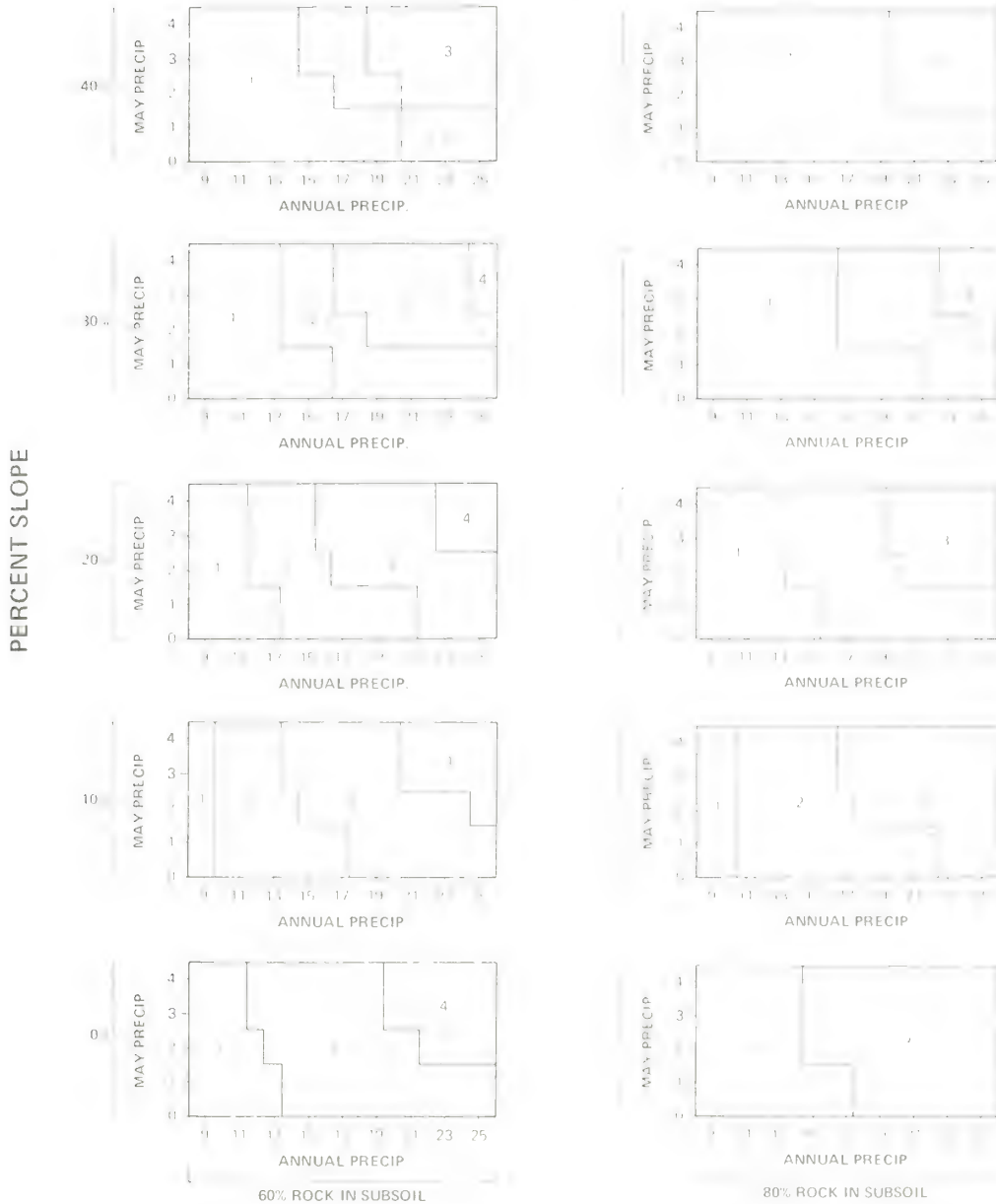
LEGEND

PRODUCTIVITY – POTENTIAL GROUPS

- | | | |
|------------------|------------------|---------|
| 1. LOW | 3. AVERAGE | 5. HIGH |
| 2. BELOW AVERAGE | 4. ABOVE AVERAGE | |

Figure 10.--Chart for determining site productivity-potential group for grass mixtures according to level of annual water-year precipitation (inches), May precipitation (inches), percent rock in the subsoil (volume; coarse fragment greater than three-fourths inch), and percent slope of area.

GRASS MIXTURES III



LEGEND

PRODUCTIVITY – POTENTIAL GROUPS

- | | | |
|------------------|------------------|---------|
| 1. LOW | 3. AVERAGE | 5. HIGH |
| 2. BELOW AVERAGE | 4. ABOVE AVERAGE | |

Figure 11.--Chart for determining site productivity-potential group for grass mixtures according to level of annual water-year precipitation (inches), May precipitation (inches), percent rock in the subsoil (volume; coarse fragment greater than three-fourths inch), and percent slope of area.

BIG SAGEBRUSH

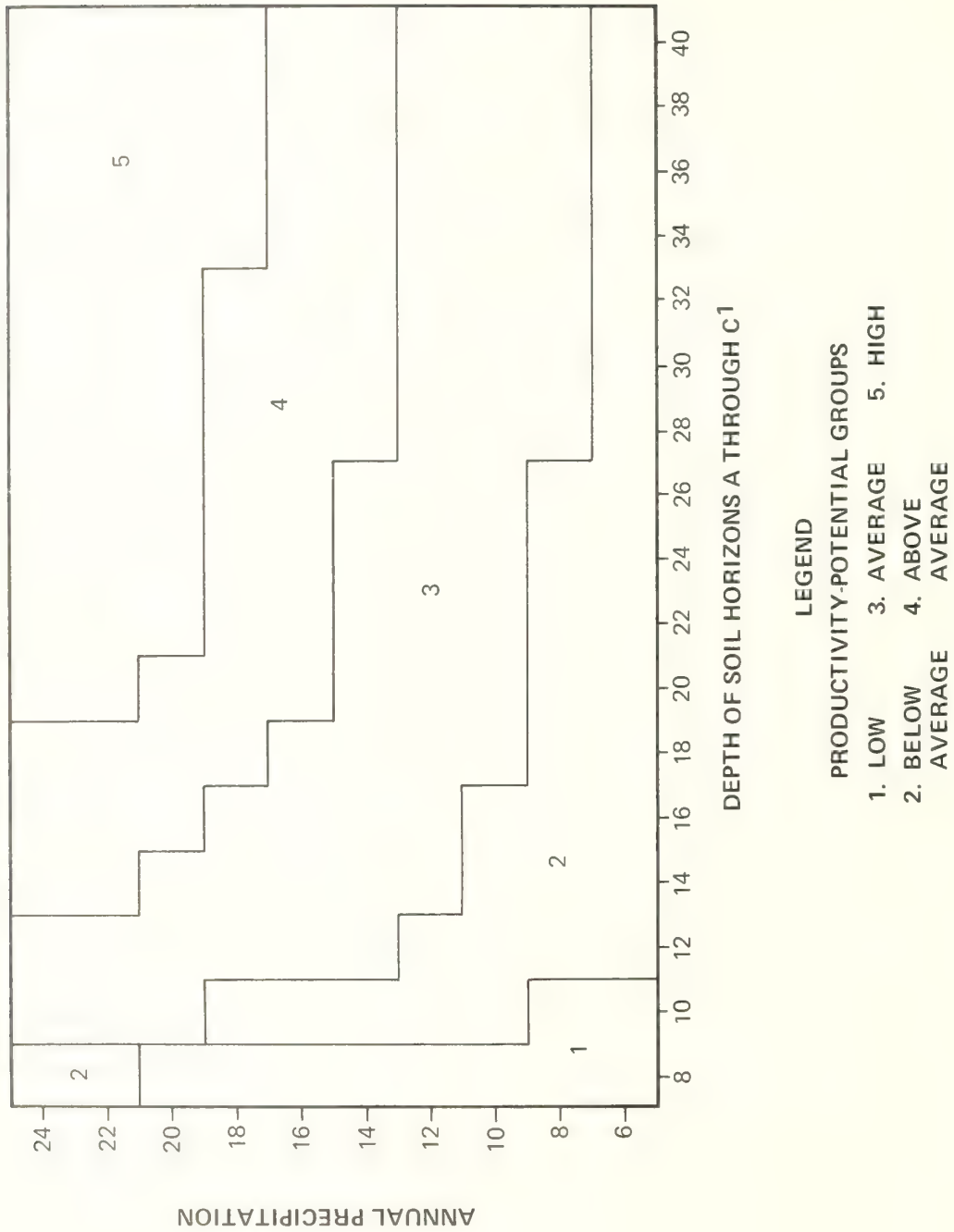
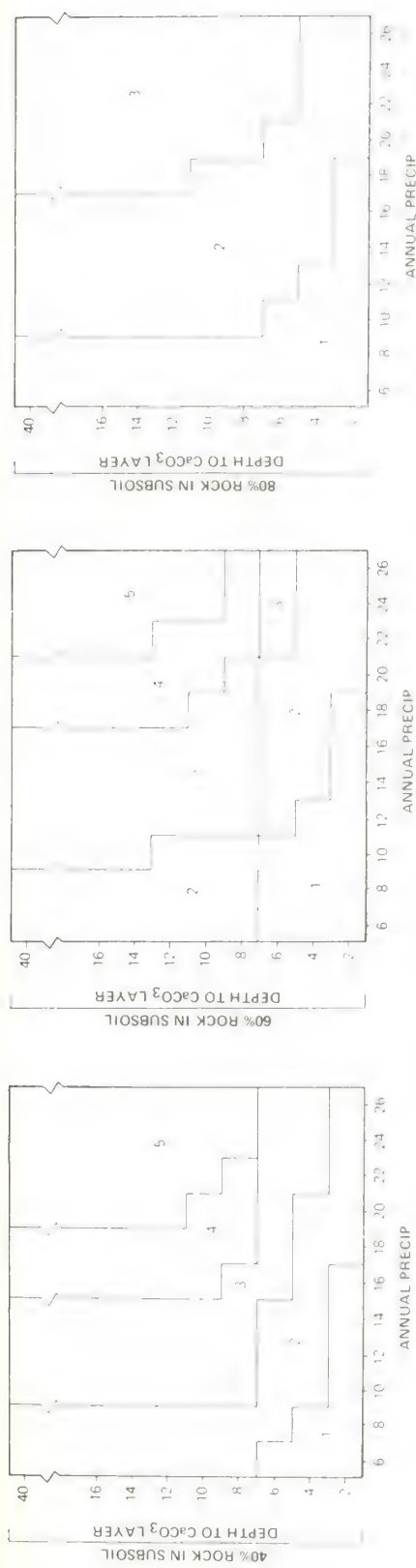


Figure 12.--Chart for determining site productivity-potential group for big sagebrush, according to level of annual water-year precipitation (inches) and depth of soil horizons A through C1 (inches).



LEGEND

PRODUCTIVITY - POTENTIAL GROUPS

1. LOW 3. AVERAGE 5. HIGH

2. BELOW AVERAGE 4. ABOVE AVERAGE

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APPENDIX I:

Derivation of Prediction Models

Interaction models were developed to represent as closely as possible the combined effects of the independent variables most strongly affecting production data for each species.

Three strongest variables for the grasses (annual precipitation, May precipitation, and percent rock in the subsoil) were included in an initial model. After the three-way interaction was accounted for, the remaining variable, percent slope, was fitted as an additive, simple linear effect.

More specifically, the data points associated with the sites were separated into all combinations of three subdivisions for the ranges of May precipitation and percent rock in the subsoil. For each of these groups, production was plotted over annual precipitation to permit examination of the three-way interaction in the light of expectation.

For the grasses, the trends were linear over annual precipitation and were fitted by approximate least deviations to the data points within each May precipitation-percent rock data group. After annual precipitation scalars were smoothed over May precipitation and percent rock data group means in accord with expectation, an algebraic descriptor was developed using curve forms and descriptor techniques from Jensen and Homeyer Matchacurves-1 and -2 (1970 and 1971) and Jensen Matchacurve-3 (1973). The resulting equation was given a final least-squares adjustment to the data points and used to provide production estimates in the production-potential charts.

The final variables adopted for big sagebrush were annual precipitation and depth of soil horizons A through C¹, while those for black sagebrush were annual precipitation, percent rock in the subsoil, and depth to calcium carbonate layer. For these two species, the modeling technique was analogous to that just described for the first three variables of the grasses.

APPENDIX II: Equations for Models

EQUATION 1

Grasses

$$\hat{Y} = 401.4 - 39.756 (SL) + 719.167 \left\{ L + \frac{(R-L)(AP-9)}{16} \right\}$$

where:

$$L = LR + LS (80-PR)$$

$$LR = 0.130 + 0.193 e^{-\left| \frac{\frac{(4-MP)}{4} - 1}{0.593} \right|^5}$$

$$LS = 0.004141 e^{-\left| \frac{\frac{(4-MP)}{4} - 1}{0.4} \right|^{10}}$$

$$R = RR + RS (80-PR)$$

$$RR = 1.90 + 1.30 e^{-\left| \frac{\frac{MP}{4} - 1}{0.55} \right|^{15}}$$

$$RS = 0.0388 + 0.07725 e^{-\left| \frac{\frac{MP}{4} - 1}{0.51} \right|^{15}}$$

Limits

9 in ≤ AP ≤ 25 in
0 in ≤ MP ≤ 4 in
0 % < PR ≤ 80 %
0 % ≤ SL ≤ 45 %

Statistics

$R^2 = 0.76$
 $S_{y \cdot x_i} \approx 1,500 \text{ lb/acre.}$
 $\bar{y} = 1,908$

Where

$\hat{Y}$ = dry-weight foliage yield of fully stocked stands, pounds per acre
AP = annual precipitation, inches
MP = May precipitation, inches
PR = percent rock by volume (greater than 3/4 inch), in the subsoil
SL = slope percent

EQUATION 2

Big Sagebrush

$$\hat{Y} = P \left(1.16050 e^{-\left| \frac{\frac{AP}{26} - 1}{0.65} \right|^{1.5}} - 0.17215 \right)$$

where:

$$P = 4692 e^{-\left| \frac{\frac{AC}{40} - 1}{0.92} \right|^3} - 896 e^{-\left| \frac{\frac{(40-AC)}{32.25} - 1}{0.1} \right|^{1.5}} - 1299$$

Limits

4 in ≤ AP ≤ 25 in
8 in ≤ AC ≤ 40 in

Statistics

$R^2 = 0.56$
 $S_{y \cdot x_i} \approx 900 \text{ lb/acre}$
 $\bar{y} = 2,045$

Where

Y = dry-weight foliage yield of fully stocked stands, pounds per acre

AP = annual precipitation, inches

AC = depth of horizons A through C¹, inches

EQUATION 3

Black Sagebrush

$$\hat{Y} = P (1.1160 e^{-\left| \frac{\frac{AP}{26} - 1}{0.58} \right|^{1.5}} - 0.1160)$$

where:

$$P = F + (B-F) \left\{ \frac{e^{-\left| \frac{\frac{(80.001-PR)}{80} - 1 \right|^N} {1-I}} - e^{-\left| \frac{1}{1-I} \right|^N}} {1 - e^{-\left| \frac{1}{1-I} \right|^N}} \right\}$$

$$F = 1532 e^{-\left| \frac{\frac{DE}{40} - 1}{0.99} \right|^{10}} - 507$$

$$B = 2892 e^{-\left| \frac{\frac{DE}{40} - 1}{0.92} \right|^{15}} - 88$$

$$N = 4.2 e^{-\left| \frac{\frac{DE}{40} - 1}{0.792} \right|^{20}} + 3.8$$

$$I = 0.41 e^{-\left| \frac{\frac{(40.001-DE)}{40} - 1}{0.18} \right|^{20}} + 0.10$$

Limits

4 in ≤ AP ≤ 25 in
0 % ≤ PR ≤ 80 %
0 in ≤ DE ≤ 50 in

Statistics

R² = 0.65
S_{y·x_i} ≈ 500 lb/acre
 $\bar{y}$ = 1,190

Where

$\hat{Y}$ = dry-weight foliage yield of fully stocked stands, pounds per acre

AP = annual precipitation, inches

PR = percent rock by volume (greater than 3/4 inch), in the subsoil

DE = depth to calcium carbonate layer

STEVENS, RICHARD, A. PERRY PLUMMER, CHESTER E. JENSEN, and BRUCE C. GIUNTA

1974. Site productivity classification for selected species on winter big game ranges of Utah. USDA For. Serv. Res. Pap. INT-158, 24 p., illus. (Intermountain Forest & Range Exp. Station, Ogden, Utah 84401.)

Productivity of a mixture of four range grasses and big and black sagebrush was correlated with soil characteristics, topography, and precipitation at 21 sites considered representative of Utah's juniper-pinyon and sagebrush-grass types. The mathematical models developed provide site evaluation guides for use in range improvement programs. Charts give productivity potential in five broad groups.

OXFORD: 182.51; 268.

KEYWORDS: site productivity, juniper-pinyon, sagebrush-grass, winter big game range, big sagebrush, black sagebrush, perennial grasses.

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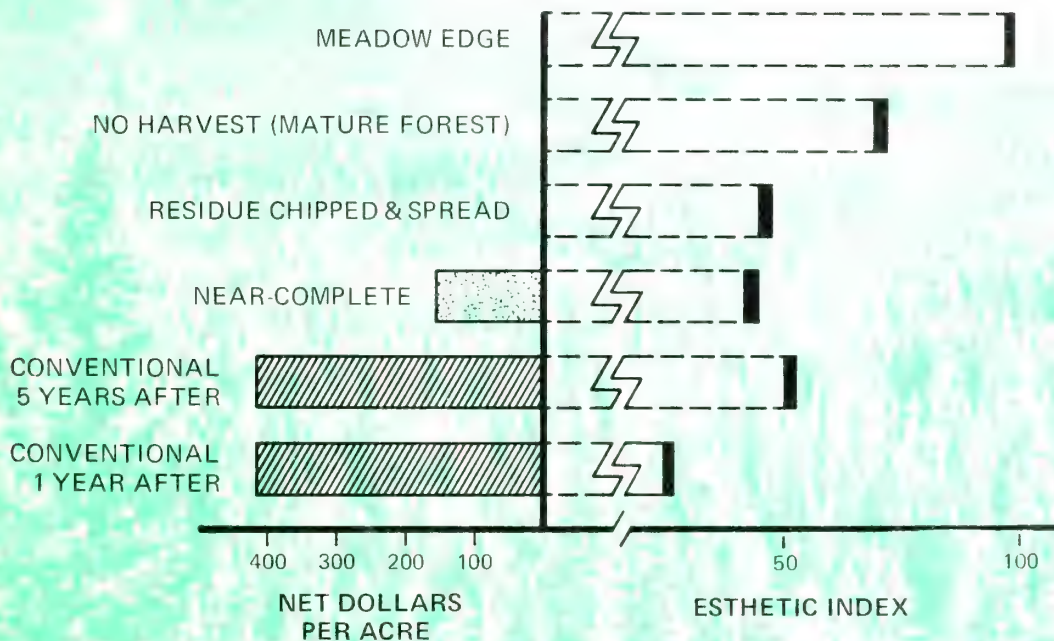
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LODGEPOLE PINE LOGGING RESIDUES: MANAGEMENT ALTERNATIVES

Hubert W. Benson



U.S.D.A. Forest Service, Pacific Northwest Research Station

UNIVERSITY OF IDAHO

FOREST SERVICE

U.S. GOVERNMENT PRINTING OFFICE

LODGEPOLE PINE LOGGING RESIDUES: MANAGEMENT ALTERNATIVES

Robert E. Benson

A Cooperative Research Study Among:
U.S. Plywood - Champion International, Inc.;
and Intermountain Region, Teton National Forest,
Intermountain Forest & Range Exp. Station,
and Forest Products Laboratory, USDA
Forest Service

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Roger R. Bay, Director

THE AUTHOR

ROBERT E. BENSON is a research forester assigned to the Forest Residues Utilization Program, and has been with the Intermountain Station in Ogden and Missoula. His research work includes studies in forest economics, wood products marketing, forest inventories and resource analysis. He served as coordinator on the study reported in this paper.

ABSTRACT

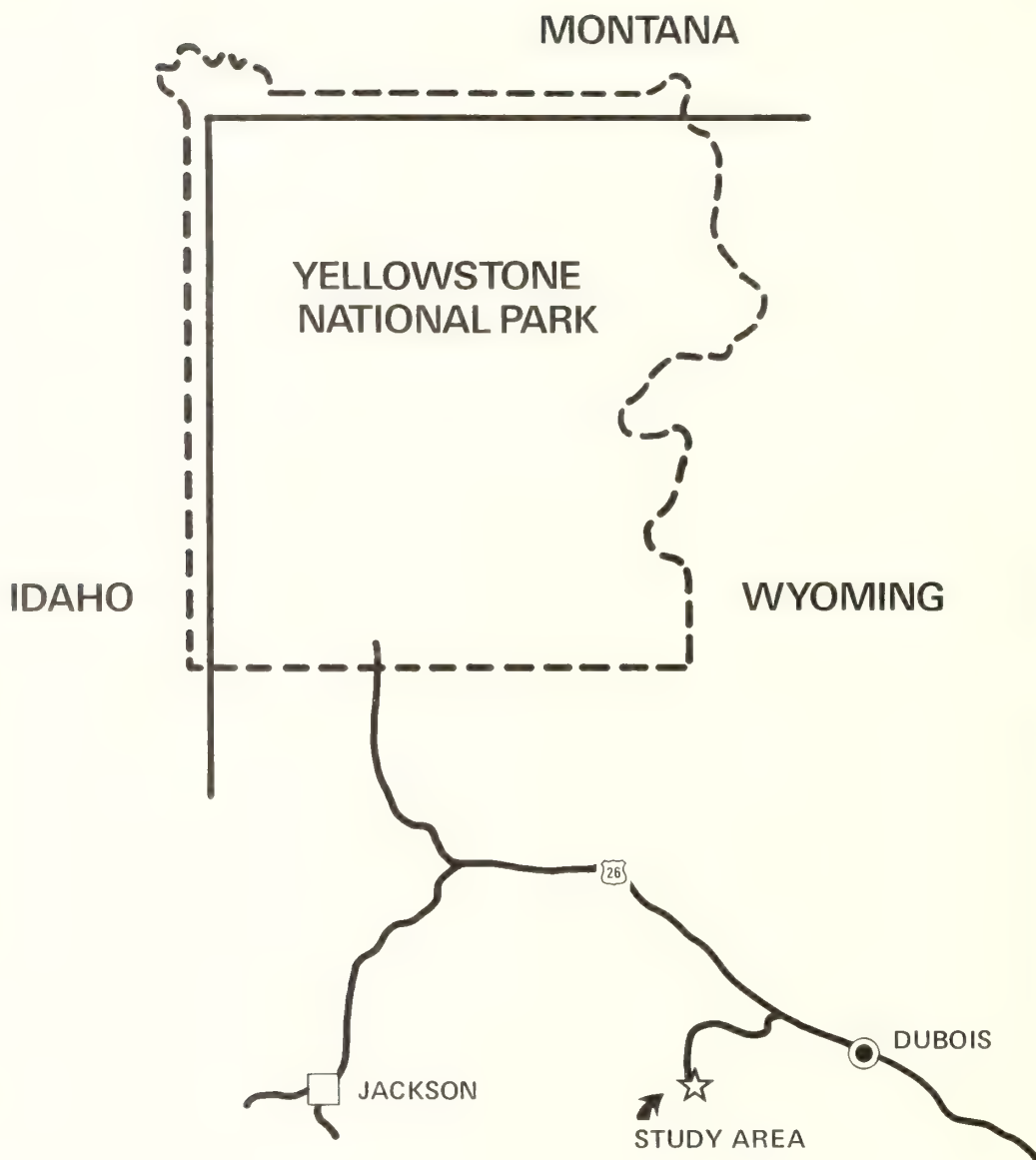
The dollar and nondollar effects of alternative levels of residue utilization in mature lodgepole pine are compared.

Net dollar returns were greater in conventional logging (removal of green sawlogs to a 6-inch top, with slash piled and burned) than in near-complete harvesting (sawlog removal followed by field chipping of remaining wood material on the site). However, substantial nondollar benefits were gained by near-complete harvesting, especially in esthetics, fuel reduction, and site preparation. Continuing studies of harvesting influences upon soils, hydrology, nutrients, and regeneration will further define costs and benefits, and will provide managers with guidelines for harvesting practice decisions.

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Lodgepole pine stands in Wyoming were harvested to conventional wood utilization standards and to near-complete utilization standards so that the economic and environmental consequences could be compared. This report, one of many being published as phases of the study are completed, explores costs and esthetics of residue management.

INTRODUCTION

In recent years there has been a growing concern over timber harvesting practices and the disposal of the resulting logging residues. Although alternative methods of harvesting and handling residues have been suggested, there has often been a lack of information on the feasibility and on the effects these alternatives might have on the forest resource and its management, and on the environment, esthetics, and related matters.

In 1971, a study was begun to evaluate a system of harvesting mature lodgepole pine (*Pinus contorta* Dougl.) in which virtually all the logging residue--branches, tops, and dead and cull material--was yarded and chipped at the logging site. The study area is located in Wyoming near the Union Pass area of the Teton National Forest. U.S. Plywood Division of Champion International and the USDA Forest Service¹ cooperated in the study.

Presently, chips produced in the study cannot be marketed locally. A critical part of evaluating the feasibility of field chipping, however, is to determine the costs and evaluate the methods for logging and chipping. In addition, the environmental and esthetic effects of logging that removes nearly all the woody material from the land are of interest. These concerns coupled with the opportunity to cooperate among the participants led to this study.

Description of Study

Four units of approximately 20 acres each were harvested by clearcutting. Two units were logged following conventional practices for that part of Wyoming. Green sawlogs to a 6-inch top were removed, and the remaining material was left for burning on the site ("green" includes recently dead trees that are sound). The other two units had "near-complete" removal; in addition to taking out the merchantable sawlogs, virtually all the remaining material was yarded and chipped. On the near-complete units, a feller-buncher and rubber-tired grapple skidder were used in connection with a mobile chipper (fig. 1). The equipment and the "near-complete" method of logging were new to the area.

The logging was completed in late fall of 1971. Postharvest treatments (described in detail later) were made in 1972 and 1973, and regeneration was completed (planting and seeding) in 1973.

¹Principal design and analysis of the study was by the Intermountain Forest and Range Experiment Station with the Teton National Forest, the Intermountain Region, and the Forest Products Laboratory cooperating. In 1973, the Teton National Forest was combined into the Bridger-Teton National Forest.

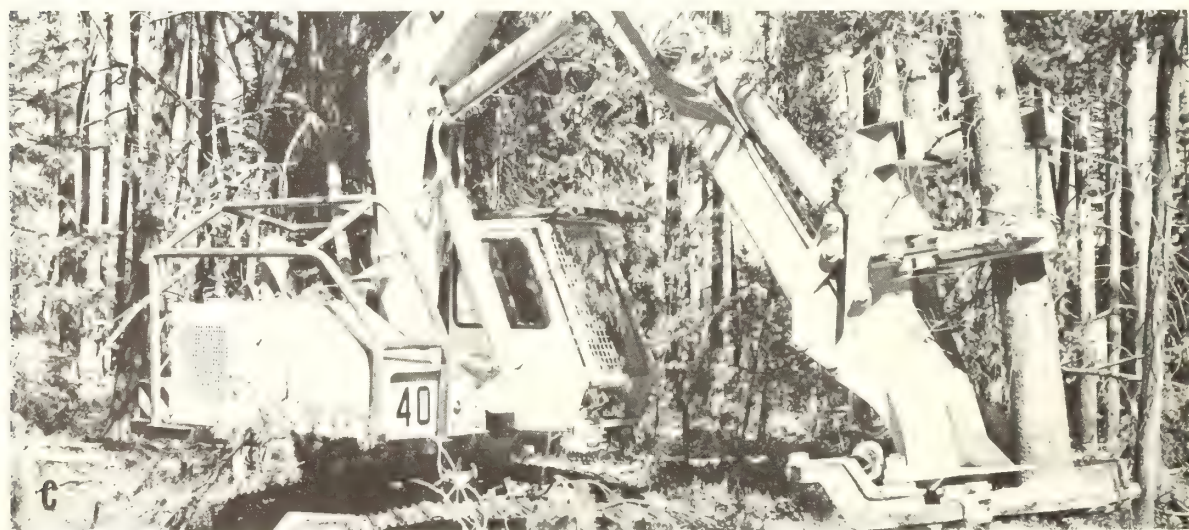


Figure 1.--Equipment used in near-complete logging in lodgepole pine, Teton National Forest: A. Grapple skidder; B. chipper; C. feller-buncher.

Evaluation of the logging areas involved a series of studies that focused on the following questions:

1. What kinds and amounts of residues remain after logging?
2. What products can be made from residues?
3. How can residues be removed efficiently for utilization?
4. What impact will removal of residues have upon regeneration and related management activities?
5. What impact will removal of residues have upon the environment, such as water quality, soil nutrients, esthetics, and wildlife?
6. What is the overall feasibility of residue removal, including both dollar and nondollar benefits and costs?

This report analyzes the benefits and costs of near-complete logging as compared with conventional logging. The results reported here must be considered in part preliminary because results for several phases of the research work will not be known until 8 to 10 years hence, and some effects of logging may still be operative several decades from now. A summary of initial benefits and costs is desirable, however, because there are many questions about the feasibility of alternative methods of dealing with logging residues that can be answered now. A discussion of this study in relation to timber harvesting problems was recently published (Galbraith 1972).

Method of Analysis

This analysis includes both dollar and nondollar benefits and costs. The actual dollar values and costs observed in the study were adjusted to take into account certain variations in study conditions and to incorporate certain assumptions that illustrate the potential of near-complete harvesting. A net value per acre was then derived for the several logging and postharvest treatments involved.

Comparing nondollar costs and benefits was more difficult. Some phases of the study were measured in physical units that provide a standard for comparison. Other phases involved judgment values either because the study limitations did not permit more formal analysis, or in some cases because no acceptable quantitative measures are available.

This analysis compares both nondollar values and dollar values for different alternatives, through a method developed by Rickard and others (1967) (fig. 2). The method illustrates the different combinations of dollar and nondollar values for each alternative, but it should be understood that this does not attach a dollar value to different levels of nondollar values.

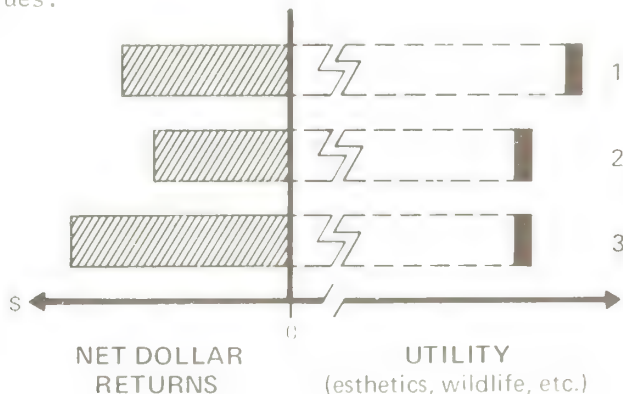


Figure 2.--Simultaneous display model of dollar and nondollar values, harvest alternatives 1, 2, 3.

NET DOLLAR VALUES

The net dollar returns per acre used in this analysis are derived as follows:

Net dollar value = (value of products on truck at landing) minus (logging cost) minus (slash disposal cost) minus (site preparation and regeneration costs).

Several net values are derived to illustrate the range of values using different combinations of logging methods and product values. The alternatives are:

Product values--one sawlog value and two chip values.

Logging method--conventional vs. near-complete.

Slash disposal methods--near-complete removal, broadcast burn, and pile burn.

Regeneration method--planting, seed spots, and natural seeding.

The actual stand volumes per acre varied among logging units. Therefore, uniform volumes per acre were assumed so that cost comparisons would reflect treatment difference.

Because logging crews using new equipment were not working with maximum efficiency, a simulated improved logging operation is included as one part of the analysis.

Value of Products

The value of products harvested was based on values of chips and logs loaded on the truck at the site. Because the timber sale was not appraised in the conventional manner, values were derived from another sale in the area. Sawlog values on the truck were \$55.71 per thousand board feet (Mbf), and chips, measured in bone dry units (BDU), valued at zero. (There is no market at present for chips in the area). Applying these values to actual volumes harvested, the value per acre from conventional logging was \$1,295 per acre, and from the near-complete logging \$836 per acre. (table 1).

Part of the difference in product values per acre is due to initial differences in volumes on the areas logged. To adjust for this, the average volume for all the units in this study (20 Mbf/acre) was assumed for alternative analyses. Harvesting operations on the near-complete units recovered only about 80 percent of the estimated initial sawlog volume. This aspect of the near-complete logging operation is discussed in more detail by Gardner and Hartsog (1973). If all the sawlogs could be recovered, and if the uniform volumes of 20 Mbf per acre are assumed, then both methods would return \$1,114 per acre for sawlogs.

Logging	Sawlog		Chips			Total Value	
	Mbf/acre:	Value/acre	Vol/acre:	Value/acre:	Value/acre:	Chips	Chips
	: @ \$55.71/Mbf:		BDU's	: \$0.301 :	\$7.00/BDU:	\$0.301	\$7.00/BDU
Actual:							
Conventional	25.2	1,295	--	--	--	1,295	1,295
Near-complete	15.0	836	47.7	14	\$341	836	1,170
Assumed:							
Uniform volume with							
80 percent sawlog recovery							
Near-complete							
Conventional	20	1,114	--	--	--	1,114	1,114
Near-complete	16	891	10	30	\$201	891	1,171
Uniform volume with							
100 percent sawlog recovery							
Near-complete							
Conventional	20	1,114	--	--	--	1,114	1,114
Near-complete	20	1,114	35	105	\$735	1,114	1,849

If chips had a value of \$7.00 per 2,400-lb BDU² on a truck at the landing, then an additional \$334 would have been obtained on the actual logging, based on 47.7 BDU per acre that were produced in the actual study. Under the assumptions of uniform sawlog volumes and 80 percent sawlog recovery, a slightly smaller volume of chips (40 BDU/acre) would have been derived, based on analysis of stand volume data. If 100 percent of the sawlogs had been recovered and uniform stand volumes are assumed, the volumes of chips would have dropped to about 35 BDU/acre; values would have been \$1,359 per acre if chips were worth \$7.00 per BDU.

Logging Costs—Stump to Truck

The actual logging costs for sawlogs were \$22.83 per Mbf on the conventional units and \$23.07 per Mbf on the near-complete units. Chipping costs were \$14.93 per BDU. Total costs were: conventional logging, \$530/per acre; and near-complete logging, \$1,058 per acre (table 2). When uniform volumes are assumed, the costs per acre are \$457 for conventional logging and \$966 for near-complete logging. If all sawlogs were recovered on the near-complete units, costs would be \$984 per acre.

Logging more efficiently on the near-complete units reduces unit costs for both sawlogs and chips by about \$230 per acre (\$966 - \$736 = \$230 with 80 percent sawlog recovery; and \$984 - \$750 = \$234 with 100 percent sawlog recovery).

Slash Disposal

On the conventional logging units, two methods of slash disposal were used. Some slash was piled with a crawler tractor and the piles burned at a cost of \$43.41 per acre; this is the usual method of slash disposal in the area. Other slash was broadcast

²Derived from \$21.00 per BDU at a manufacturing plant (average chip price at western mills), less 10 percent screening loss, less \$11.90 hauling cost from site to plant.

Table 2.--Logging costs--stump to truck for actual study conditions and for assumed volumes and simulated logging operations¹

Logging	Sawlogs			Chips			Total cost/acre
	Vol/	Cost/	Cost/	Vol/	Cost/	Cost/	
	acre	Mbf	acre	acre	BDU	acre	
	Mbf	---Dollars---		BDU	-----Dollars-----		
Actual Harvest (ave.):							
Conventional	23.2	22.83	529.66	--	--	--	530
Near-complete	15.0	23.07	346.05	47.7	14.93	712.16	1,058
Assumed:							
Uniform Volume							
Conventional	20	22.83	456.60	--	--	--	457
Near-complete	16	23.07	369.12	40	14.93	597.20	966
(80% sawlog recovery)							
Uniform Volume							
Conventional	20	22.83	456.60	--	--	--	457
Near-complete	20	23.07	461.40	35	14.93	522.55	984
(100% sawlog recovery)							
Favorable logging							
Conventional	20	22.83	456.60	--	--	--	457
Near-complete	16	17.70	283.20	40	11.33	453.20	736
(80% sawlog recovery)							
Favorable logging							
Conventional	20	22.83	456.60	--	--	--	457
Near-complete	20	17.70	354.00	35	11.33	396.55	750
(100% sawlog recovery)							

¹Costs per unit of product derived from Gardner and Hartsog 1973. Volumes per acre from Gardner and Hann 1972, and from assumed volumes.

burned with no treatment except that a fireline was made with a crawler tractor at a cost of \$18.67 per acre (table 3). Although the broadcast burning costs less than piling and burning, favorable burning conditions are limited in duration. (A more detailed discussion of broadcast burning is presented later.)

On the near-complete logging area, part of the slash was left "as is" after the logging, with no further cleanup. In the analysis that follows, this treatment is assigned zero cost (but alternatively a portion of the logging cost could be assigned here). On part of the area, chips were spread back on the ground about 4 to 6 inches deep to study the effects on planted seedlings, soil nutrients, and so on.³

³The method of putting chips on the ground would not likely be used in general practice; therefore, the actual costs incurred are not included in the analysis.

Table 3.--Costs of postharvest activities

Activity	Conventional		Near-complete	
	Broadcast burn	Pile and burn	Chip "as is"	spread
SLASH TREATMENT				
Piling/fireline	4.86	35.71	0	0
Burning	11.85	1.94	0	0
Overhead	2.48	5.76	0	0
Total costs	18.67	43.41	0	0
REGENERATION				
Natural seeding	0	0	0	0
Planting ¹	122.89	133.48	156.92	146.00
Seeding ¹	75.33	61.12	66.93	53.05
REGENERATION AND PROTECTION, TOTAL COSTS ²				
Natural seeding	64.50	64.50	64.50	64.50
Planting	187.39	197.98	221.42	210.50
Seeding	139.83	125.62	131.43	117.55

¹Includes stock and seeds, overhead, and mouse control.

²All totals include \$61.50 per acre, cattle fencing; \$3/per acre, gopher control.

Site Preparation and Regeneration

Three regeneration methods were used on the logging units: planting 2/0 trees (700/acre), seed spots (10 seeds/spot, 1,000 spots/acre), and natural regeneration. Ground cover was "scalped" with a McCloud tool or hazel-hoe, then auger-planted or seeded with a panama seeder. The costs per acre are shown in table 3.

The differences in planting and seeding costs reported may in part be due to different treatments, but because there were only two replications, it was not possible to isolate other variables (weather conditions, training of crews, etc.). Actual costs are used here, but it is likely that over many replications cost differences between treatments would be small or not significant (see later section on regeneration).

The regeneration costs apply only to the initial planting and seeding. If new trees fail to become established and subsequent replanting or reseeding is required, regeneration costs would need to be revised upward. For comparison, in 1972, on the Teton National Forest average regeneration costs were \$178 per acre (site preparation and planting), and the survival rate at 1 year about 82 percent.⁴

⁴Memo of May 24, 1973, 2470 Silvicultural Practices, Assist. Reg. Forester, Timber Management, Ogden, to Forest Supervisors, Table A.

Seeding on the adjacent Bridger National Forest had 64 to 72 percent stocked seed spots after 3 years, using methods like those in this study (Lotan and Dahlgreen 1971).

Summary of Dollar Values

When values and costs presented above are summed to net dollar values, several dozen possible combinations could be made and would show a wide range in dollar values (fig. 3). Actual values on the near-complete units average -\$443 per acre. At the other extreme, values for near-complete logging assuming uniform volumes, 100 percent recovery of sawlogs, most favorable logging conditions, and chip values from conventional logging are greater than from near-complete logging under all conditions analyzed.

For purposes of the display model, only one set of net values is used. (Appendix table 4 shows alternative values that could be inserted in the dollar side of the model). Values used are based on uniform volumes per acre, 100 percent sawlog recovery, and \$7.00 per BDU chip value. It is assumed that near-complete logging of this kind would not be undertaken unless the chips would be removed and utilized, and that sawlog values are such that every effort would be made to recover all merchantable sawlogs.

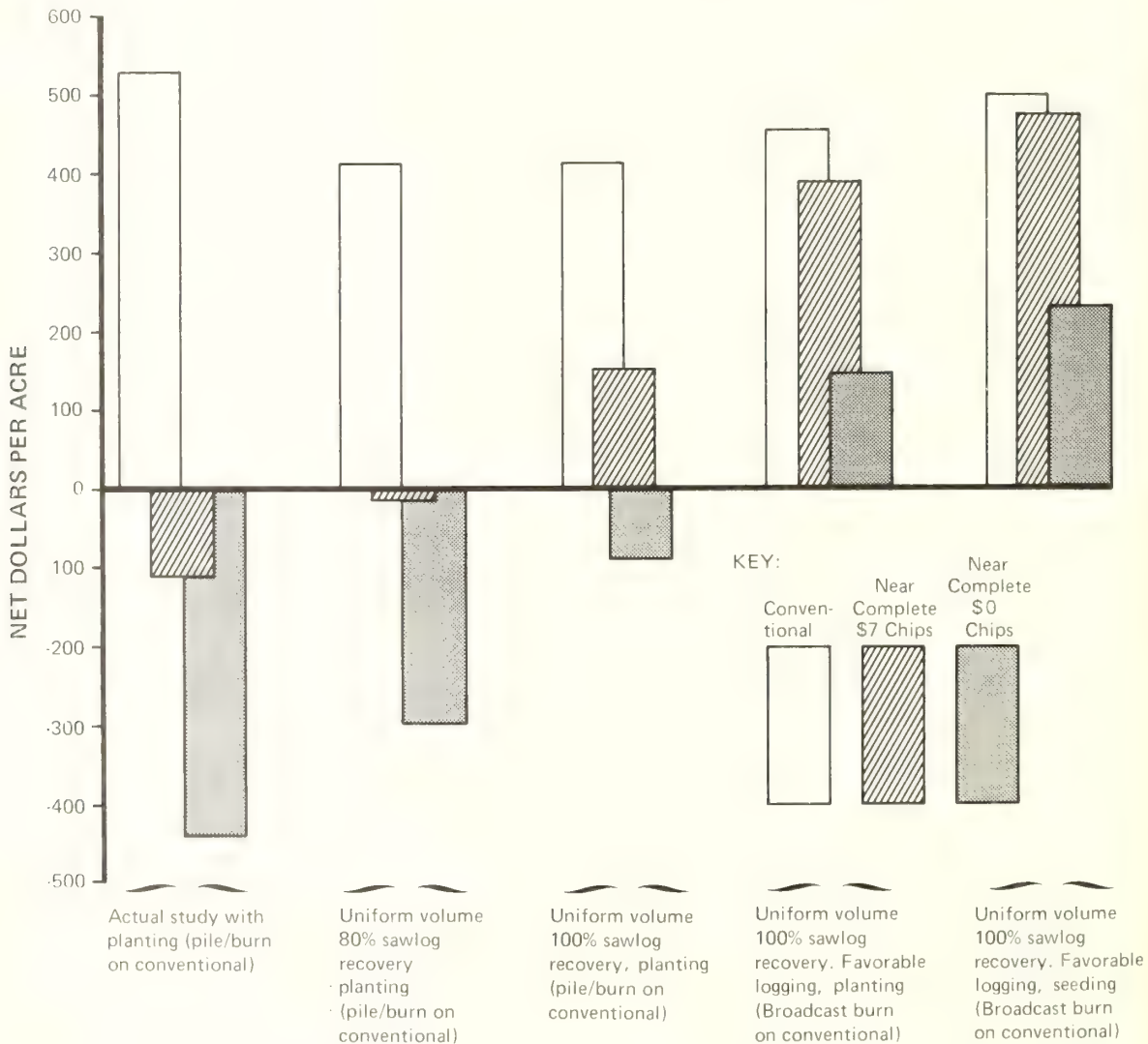


Figure 3.--Net dollar values per acre for various logging and postharvest treatments.

Piling and burning is used in the conventional logging, and planting is assumed on both conventional and near-complete logging sites. Broadcast burning and either seeding or natural regeneration might reduce costs, but at present these methods are not generally used. The net values per acre used in the remaining analyses are:

Conventional	Dollars
Product value	1,114
Logging cost	-457
Slash disposal (pile/burn)	- 43
Regeneration (planting)	-198
Net dollar value per acre	416

Product value (chips = \$7)	1,359 (chips = \$14.50)	1,621
Logging cost	-984*	-984
Slash disposal	0*	0
Regeneration (planting)	-221	-221
Net dollar value per acre	154	416

*Alternatively, logging cost could be \$984 - \$43 = \$941, and slash disposal could be \$43. Net values per acre would remain the same.

If chip values were \$14.50 per BDU, the net dollar value per acre of conventional and near-complete logging would be the same.

These net dollar values are shown in the display model in figure 4. The value of "no harvest" (assumed to be zero) and of chip spread treatment (a negative value of some indeterminant amount) are also shown because an esthetic evaluation and some other evaluations were made for these treatments.

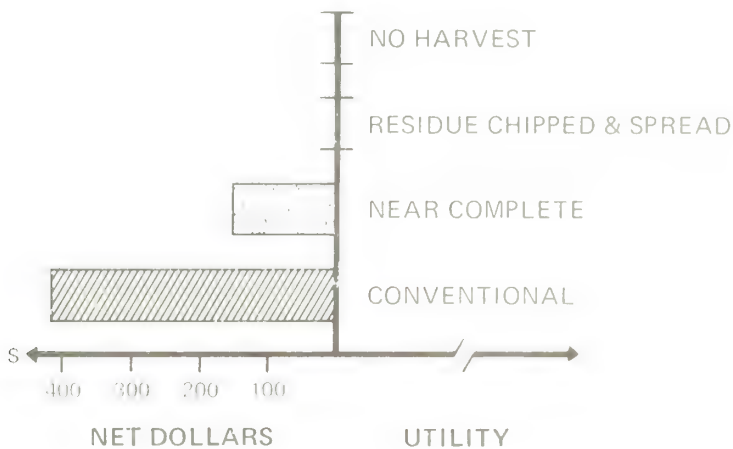


Figure 4.--Net dollar values of alternative harvest and post-harvest activities.

ESTHETIC EVALUATION

A prime objective of this study was to compare the logging and residue treatments in terms of esthetics. Since the principal concern is for differences among treatments, evaluation was based on the viewpoint of an observer hiking or driving alongside the harvested units. No evaluation was made of the distant-view esthetics, such as how well the units conformed to the general landscape; these are of course important for any logging or treatment used.

Two types of esthetic evaluations were made. In one evaluation, Forest Service landscape managers appraised the area. Two facets were considered: a general evaluation of different treatments to provide a numerical rating, and an analysis of specific features within the units.⁵ This is referred to as "manager's evaluation." The other evaluation was made by university students who viewed slides taken at random in each of the areas and rated them as to degree of "like" or "don't like." This is referred to as "laymen's evaluation."⁶



Figure 5.--Manager's esthetic evaluation, mature lodgepole pine stands (vantage point: driving by area, foreground).

⁵General evaluation was made by Reed Stalder, landscape architect, Intermountain Regional Office, Ogden, Utah. Analysis of features was made by Walt Grubic, landscape architect, Teton National Forest.

⁶This evaluation was made by Ron Boster, Rocky Mountain Forest & Range Exp. Station, Tucson, in conjunction with staff members in the Dep. Psychology, Univ. Arizona, using Theory of Signal Detectability Techniques. Laymen were drawn from university students.

Manager's Evaluation

The manager's rating of treatments is shown in figure 5 and compares an uncut old-growth stand, conventional (pile and burn) cleanup, near-complete (residue removed), and chips spread over the ground. In addition to the rating immediately after harvest (year 0), projections were made as to esthetic response 10 and 20 years hence.⁷ The evaluation was based on what would be seen when driving by the areas. Other evaluations were made for activities such as 1-day visits, and other recreation activities. In general, the relationship between treatments was about the same, although activities in which the observer was at the area for some period of time rated lower than for the observer just driving by.⁸

The uncut old-growth stand rated highest at the year of harvest, but is expected to decline over time, as tree mortality and blowdown bring a more ragged and dilapidated appearance. Near-complete residue removal areas rated fairly high after harvest and, assuming normal regeneration, are expected to reach a high (100 index) level in 20 years. Pile-and-burn areas also are expected to show recovery, but will remain below the esthetic values of the near-complete residue removal areas.

The comparison of the pile-and-burn vs. residue-removed treatments noted several features:

1. Near-complete units had an overall clean look compared to cluttered look of pile-and-burn units.
2. Soil disturbance on near-complete units was not excessive, but on piled areas created visual discord.
3. Low stumps on the near-complete units (resulting from the shearing near groundline by the feller-buncher) created less discord than stumps on the conventionally logged pile-and-burn unit.
4. Good herbaceous cover was retained on the near-complete blocks, which kept the color tone compatible with surrounding area.

These factors tend to substantiate the higher ratings given to the near-complete unit. The near-complete unit rated higher than the conventional unit for all the other vantage points and types of use that were used in the evaluation.

Using the model outlined earlier, the esthetic values and dollar values are displayed in figure 6.

⁷Projections for 10 and 20 years hence are based on the expectation that plant succession and growth will be similar to that in adjacent areas where development following disturbance has been observed.

⁸Complete results are not shown here, but are summarized in Office Report "Wyoming logging residue study, esthetic and recreation evaluation," by Reed Stalder, on file at Intermountain Forest & Range Exp. Station, Forestry Sciences Laboratory, Missoula, Montana.

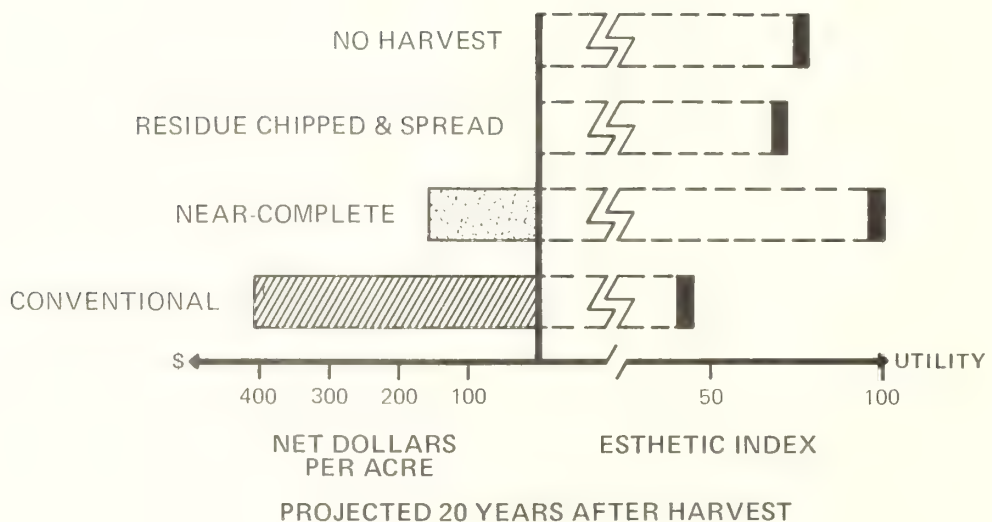
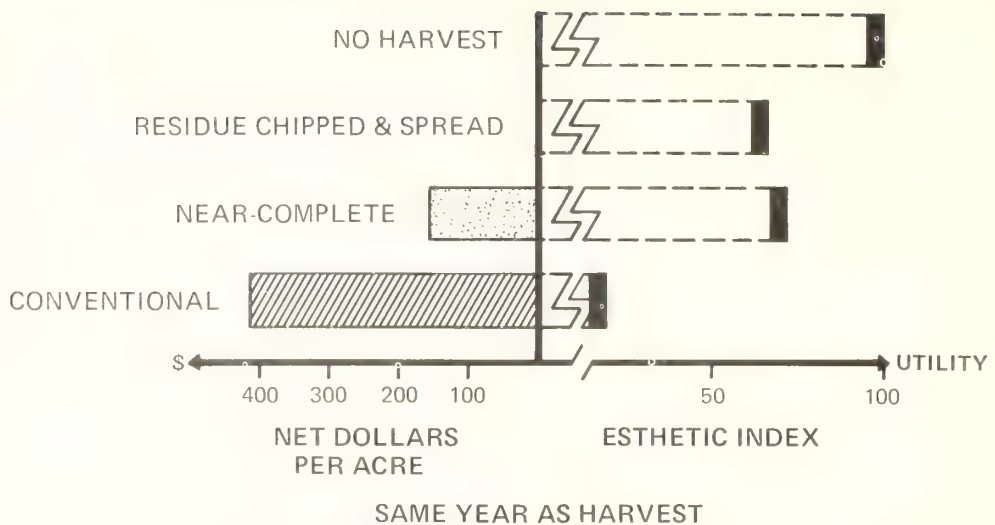


Figure 6.--Net dollar values and manager's esthetic evaluation.

Laymen's Evaluation

In the laymen's evaluation, slides of six different "treatments" were shown to panel groups and their ratings for each slide were recorded. The treatments included: a meadow-forest edge, which served as a benchmark because of its known high esthetic appeal; a pile-and-burn area 5 years after treatment; near-complete removal; chip-spread area; pile-and-burn 1 year after treatment; and an uncut stand.

The raw data obtained from the laymen's evaluation are presented in the following tabulation. The median rating means half the viewers rated the treatment higher, and half lower than the value shown. (These values are based on a 0 to 9 ranking, with 0 = strong dislike, 9 = strong like, 4 = just guessing "I dislike," 5 = just guessing

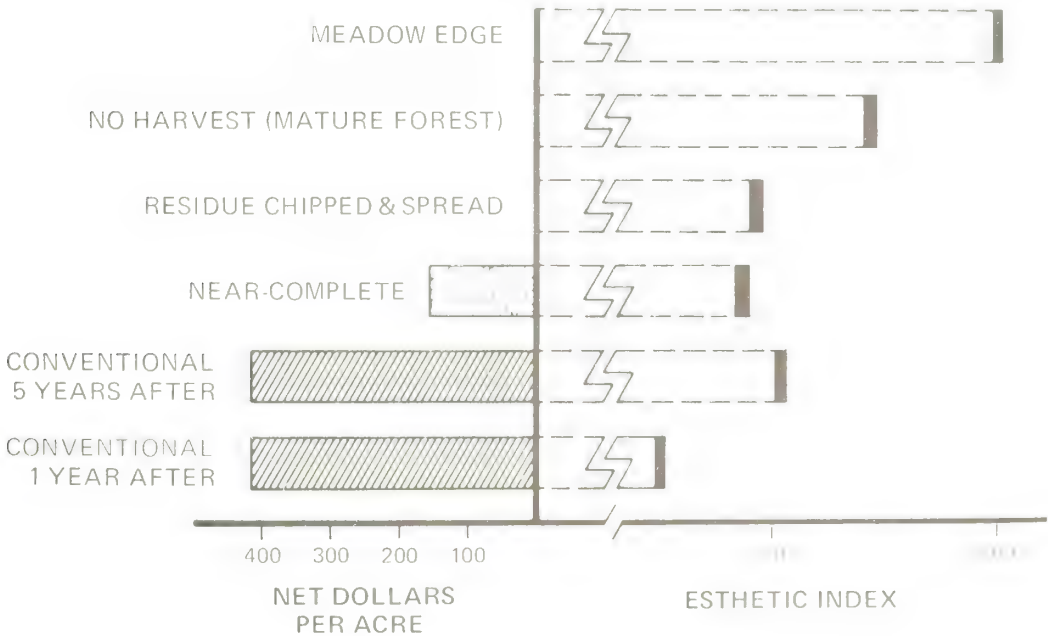
"I like," etc.). The scenic value estimator (SVE) compares a particular treatment when compared to the most pleasing (meadow-forest edge), which was set at zero. The SVE score is a statistically unbiased standardized measure of people's relative preferences for a given treatment (Boster and Daniel 1972; Daniel and others 1973).

The ratings below are averages of values given by two groups of laymen:

Meadow edge	0	8.00	100
Unharvested forest	.65	5.85	73
Pile & burn, 5 years after	1.00	4.00	50
Near-complete removal	1.00	4.00	50
Chips spread	1.00	4.00	50
Pile & burn, 1 year after	1.75	2.25	27

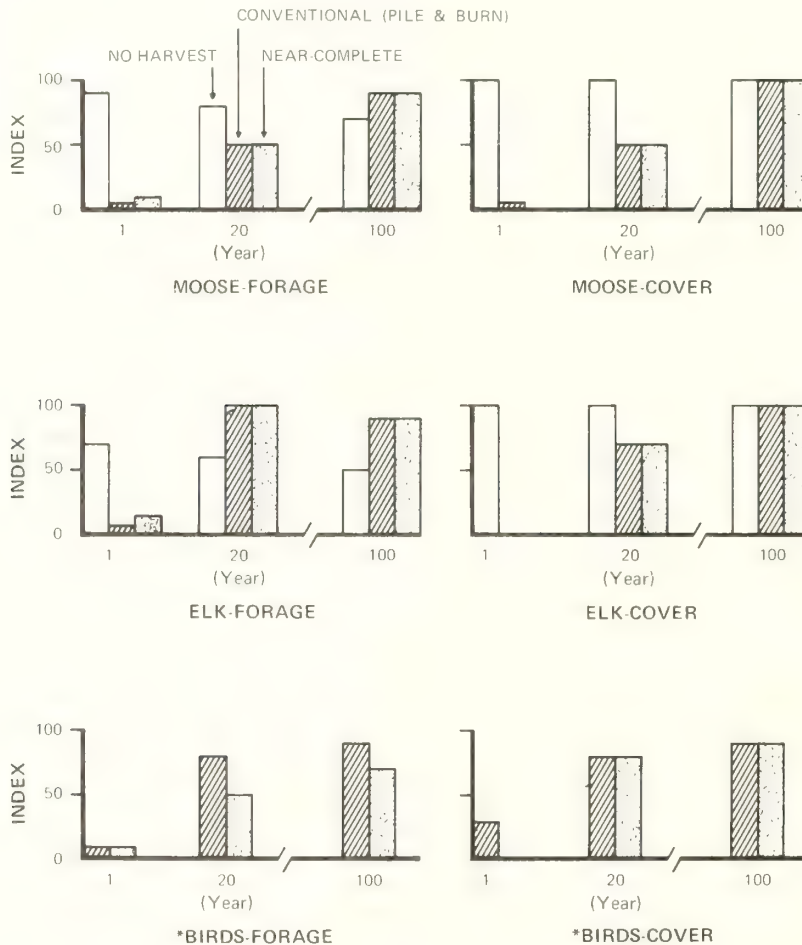
The median ratings are not directly comparable to the SVE scores, but these two measures do show approximately the same relationships among treatments. To make the laymen's rating comparable with the manager's rating, the median rating was converted to a 0-100 scale index. The laymen's esthetic indexes are shown with dollar values in figure 7.

Admittedly, esthetic measurements like those shown above cannot be precise. It is significant, however, that the general ratings of these treatments by both laymen and managers are similar.



WILDLIFE EVALUATION

In 1972, the Teton National Forest Wildlife biologist evaluated the areas in terms of effects on wildlife. Field sampling and observations of both wildlife and vegetation were combined into an index value for three time periods (at harvest, 20 years hence, and 100 years hence).⁹ The ratings developed for moose, elk, and birds for three treatments are shown in figure 8. Additional analyses of vegetation counts and of other treatments are summarized in an unpublished report.¹⁰



* "No harvest" -- not evaluated for birds.

Figure 8.--Wildlife index values at harvest and projected 20 and 100 years hence.

⁹Projections for 20 and 100 years are based on the expectations that plant succession will be similar to that of adjacent areas, and further assumes that other things remain equal.

¹⁰Processed report under cover letter of George Gruell, Wildlife Biologist, Teton National Forest to Jack Hougaard, Regional Planner, Ogden, Utah, June 15, 1973.

For moose and elk, principal game animals of the area, the two postharvest treatments were virtually the same in terms of forage and cover. Unharvested stands are superior to both harvesting treatments in terms of cover, but over time forage is projected to increase on harvested areas and decrease on unharvested stands. Habitat in piling and burning areas was superior to near-complete removal areas-in providing perching places and in the amount of food produced. Potential damage by pocket gophers was also evaluated; this is discussed in the regeneration section.

Although these evaluations were of necessity largely subjective, both postharvest treatments were judged to offer little forage and cover for big game. The chip-spread areas were judged to offer even less in vegetation response and wildlife potential. On the other hand, within 20 years both treatments are projected to make substantial response in cover, and are expected to surpass unharvested areas in forage produced.

The utility index values and dollar value comparisons vary among wildlife species and time period but figure 9, based on elk forage and cover, could be considered a representative basis for comparison.

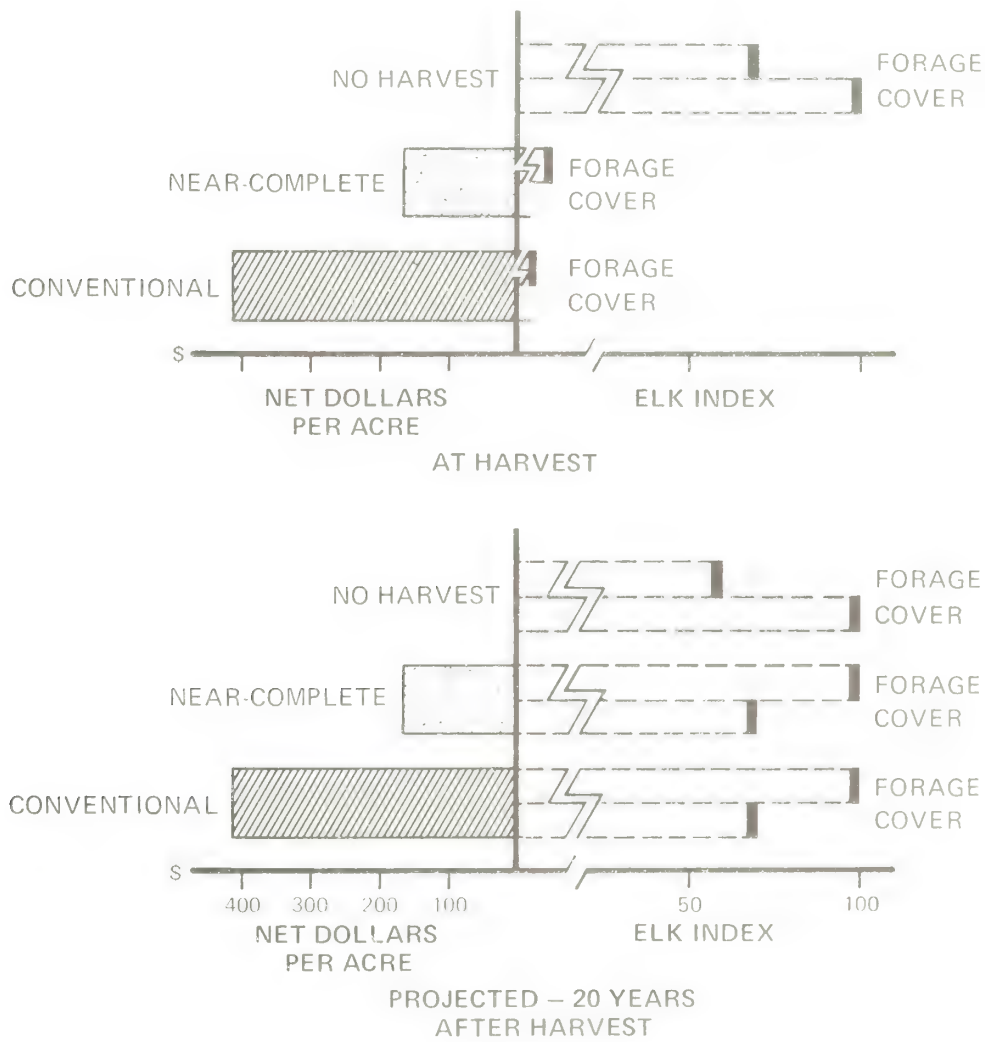


Figure 9.--Net dollar value and utility index for elk forage and cover.

PRELIMINARY REGENERATION EVALUATION

Seeding and planting were completed in June 1973. Although it is too early to adequately evaluate effects of treatments on regeneration, certain items are now evident.

The costs of planting or seeding the four treatments are probably not significantly different. Weather conditions, training of crews, and other factors have entered in differences reported here.

Overall, seedling survival the first growing season was high--over 95 percent for all areas planted. Germination of the spring-sowed seed spots was delayed until well into August. On the average there are two to three germinates per seed spot and about 55 percent of the spots are stocked, but results are highly variable.

The spreading of chips as an alternative to burning could present problems. Soil-surface temperatures will probably be significantly lower on areas spread with chips than on other treatment areas, and this is going to affect seedling development on this high elevation site.

Regeneration and survival in this area are affected by pocket gophers, which gnaw the roots of young seedlings, and by various seed-eating rodents and birds.

First-year observations on both the near-complete and conventional units showed few pocket gophers within the units. In addition, seed-eating birds and animals, particularly red squirrels and chipmunks, were mostly seen on the edges of the units. Future evaluations will be needed to learn if there are differences in regeneration between the two logging systems that can be attributed to birds or animals.

If these initial observations hold throughout the next few years, the differences between treatments will be small in terms of dollars, and except for the chip-spread areas, nondollar values (i.e., survival and possibly, growth) will also be similar. In other words, the utility index "bars" on the model should remain about the same.

On the other hand, if subsequent years show differences in growth or survival, then the utility indexes should be adjusted. If survival were unsatisfactory and re-planting or reseedling were needed, these results could also be incorporated directly in the net dollar values.

FUELS, FIRE HAZARDS, AND BURNING

Following logging and before any cleanup work, fuels and fire hazards were compared for the two treatments. Preharvest and postharvest inventories on the amounts and compactness of fuels provided data that were used to predict fire intensity and rate of spread (Brown 1974).

The weight of fuels on the ground on the near-complete units was reduced to about one-third of the preharvest level, and increased about three times on the conventional units. The amount and compactness of fuel used as inputs for a mathematical fire model indicate that on the conventionally logged area (before any piling of slash) the rate of spread would be about 4-1/2 times greater and the intensity about 3-1/2 times greater than on near-complete harvest areas.

In practical terms this means that some type of slash treatment would likely be needed to reduce hazard on slash left after conventional logging, but it would not be needed on near-complete areas. If prescribed burning were desired for regeneration or other purposes, however, the near-complete areas would be difficult to burn.

The principal nondollar factors considered in burning vs. not burning are soil disturbance in piling, air quality, heat damage to adjacent stands, and the risk of a fire escaping control.

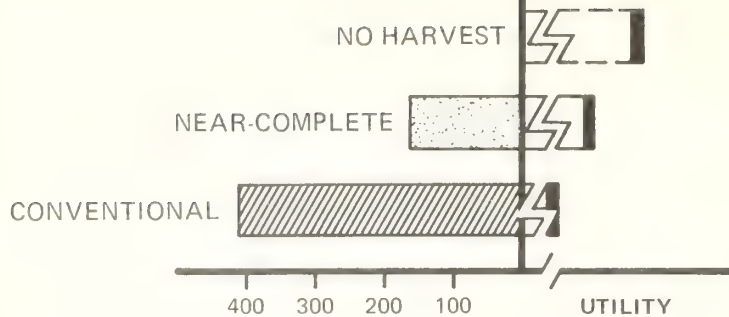
Assessing impact of piling on the hydrology, soil micro-organisms, and nutrients will require several years of observation. The esthetic evaluation noted, however, that disturbances such as pushing dirt into the slash and gouging the ground detracted from the appearance of the piled units. This is a common occurrence in piling, particularly if the ground is wet.

If smoke from slash burning was highly intolerable to people in the area, then the near-complete logging would have infinitely greater utility. Either there would be laws against such burning or managers would simply not choose to burn. This is not the case in the study area. The location and the air movements are such that under normal conditions only the few people visiting this rather remote area would be aware of the burning. Because of this, there is probably no significant difference in utility between burning and not burning as far as smoke is concerned.

Along the edges of the areas that were broadcast burned, some trees were scorched, but not on a scale that would be of concern. The probability of an escape fire is small because managers would not be burning under hazardous conditions and because fires seldom occur in these high-elevation lodgepole stands. Broadcast burning is not commonly used in the area, however, because seldom are burning conditions favorable enough to produce desired results.

Taking these factors into account, near-complete logging with no burning may have some indeterminate but small advantage over burning. This assumption is modeled in figure 10.¹¹ This analysis assumes that burning would be avoided under conditions that

¹¹The analysis of burning is based on observations by Rod Norum, Northern Forest Fire Laboratory, Missoula, Montana, on burning conditions and prescription (Wyoming residue study burn prescription, April 3, 1972, memo) observations of Teton National Forest personnel, and personal observations of burning and postburn conditions.



and utility index of
hazard reduction and
burning.

were either too wet or too dry, windy, or otherwise hazardous. It should be recognized also, that this analysis applies only to the fuels and burning aspects. Wildlife and esthetic values are affected by the fuels treatment but these values are incorporated into the model elsewhere.

HYDROLOGY, SOIL, AND NUTRIENTS

A critical part of this study is to determine the effect of near-complete utilization on the soil and water regimen. Several studies are underway and will continue to 1976 or 1977. These include analysis of soil structure and properties, soil chemistry and biochemistry, nutrients, hydrologic and erosional behavior, and vegetal characteristics.¹²

These studies have two goals: (1) comparing near-complete logging with conventional logging in terms of soil compaction and disturbance, and (2) learning how removing a large part of the stand affects the nutrient system.

This information is extremely important to land managers charged with both the protection of the environment and the production of timber products from forest lands. Therefore, the benefits and costs outlined in this report could be altered if the two harvesting systems have markedly different impact on soil, water, and nutrients.

¹²Detailed study plans on file at Forestry Sciences Laboratory, Logan, Utah:
Evaluating hydrologic and soil stability effects of logging residue disposal in lodgepole pine forests in Wyoming (Paul Packer)
Regeneration of lodgepole pine and nutrient status of areas logged with varied utilization standards in Wyoming (James Lotan)

Appendix A--Nutrient sampling (Norbert DeByle)

Appendix B--Effects of chemistry on soils and subsurface water (Alvin Southard, Richard Hawkins, George Hart, and Norbert DeByle)

Appendix C--Effects on biochemistry of soils (John Skujins and Norbert DeByle).

UTILIZATION OF RESIDUES

A major objective of this study was to examine the feasibility of using the logging residues. Because there is no chip-using industry in the area, it was not possible to follow through on an operational basis; however, the Forest Products Laboratory evaluated suitability of the chips for various wood products.

Several particleboards were made from residues, including a three-layer structural board that was 50 percent slivers from the field-chipped residues and 50 percent flakes from roundwood bolts (fig. 11). Initial tests indicated that structural boards can be readily manufactured from lodgepole pine residue (Heebink 1974).

Residues from the area were characterized in terms of live and dead material, and volume of wood and bark. As shown by the following tabulation, the residues 3 inches

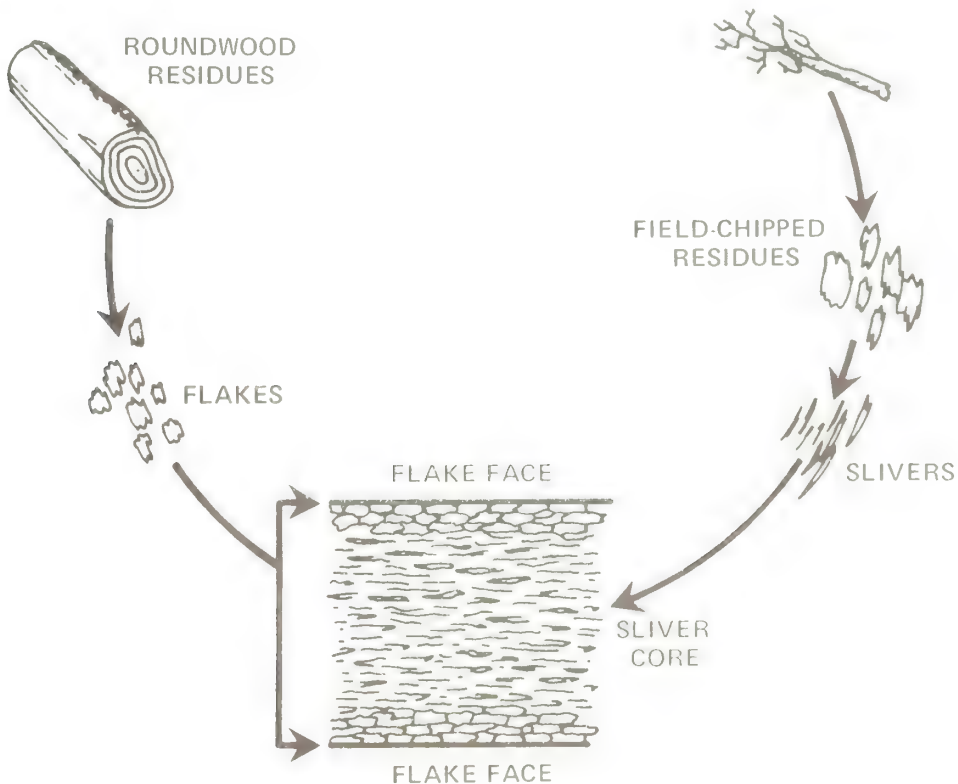


Figure 11.--Three-layer lodgepole pine particleboard made from logging residues.

in diameter and larger had about 9 percent bark by volume, and the smaller size material had somewhat more bark (Foulger and Harris 1973).

<u>Diameter size class</u> (Inches)	<u>Residue volume</u>		
	<u>Wood</u>	<u>Bark</u>	<u>Total</u>
	- - - - - Ft ³ per acre - - - - -		
<0.3	2.4	5.7	8.1
0.3 to 0.6	69.3	41.2	110.5
0.6 to 3.0	562.7	84.8	647.5
>3.0	3,274.5	292.5	3,567.0
Total	3,908.9	424.2	4,333.1

With current operating practices, most pulp mills would desire some separation of bark and chips for making paper. The technical requirements and economic feasibility of pulping chips were beyond the scope of this study. Because lodgepole pine wood has good pulping properties, pulping is a potential use for field residues.

Chips spread on a work road at the logging site made it easier to drive over spots that collected water. However, the chips held frost and moisture longer than adjacent bare ground. Chips hauled to a local rodeo ground and a campground provided a clean cover that reduced dust during the 2 years observed.

The benefits and costs of utilizing the residues have largely been incorporated in the cost analysis section. In addition to the direct costs and returns, the extent to which residues can be manufactured into substitutes for lumber and plywood, both in heavy demand, will be of interest. A given acre of lodgepole pine might produce not only the dimension lumber for framing a house, but also much of the panel material needed for sheathing. Additional testing and market development would be needed to implement structural lodgepole pine particleboard, a potentially important and promising way to utilize these residues.

Assuming that wood fiber is equally useful for different types of structural materials, the percentage of fiber recovered can provide a simple utility index.¹³ In the study area, the total volume of fiber for different logging methods averages about 10,000 ft³ per acre. In conventional harvesting, about 65 percent of this material was removed; in near-complete harvesting, about 97 percent. Figure 12 shows an index of fiber use under these alternatives.

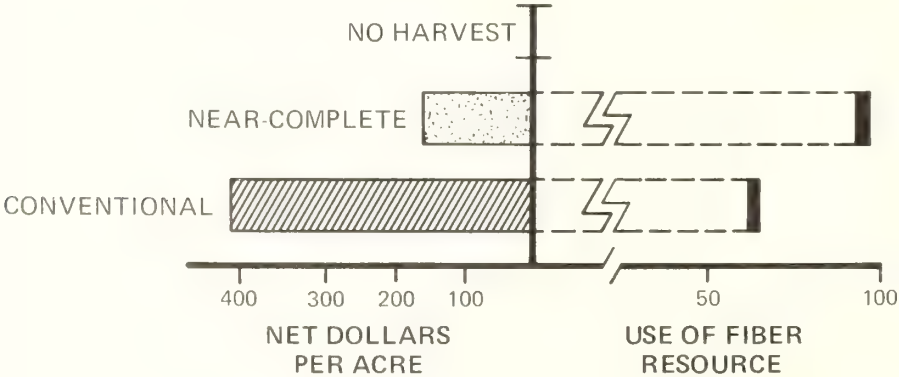


Figure 12.--Index of utilization of wood fiber.

¹³The price per cubic foot of lumber, plywood, or particleboard varies with grade, markets, etc., but can be considered reasonably close to equal for materials that would be used in most construction.

SUMMARY

Analyses have compared nondollar values with the net dollar values of different harvest and postharvest alternatives. Individual nondollar values can now be brought together and displayed simultaneously to form a composite model (figure 13).

It must be remembered, however, that the nondollar values expressed along a utility index from 0 to 100 do not necessarily have equal importance. In a given situation, for example, the wildlife considerations may overshadow any of the other nondollar values involved.

When this happens, quantitative analysis must stop and the judgment of the land manager must take over. The model has systematically displayed the various dollar and nondollar benefits and costs, recognizing a given value. The meaning and the weighting of each must be tied to specific situations. A similar type of logging applied with different species, terrain, or other conditions could greatly alter both the dollar and nondollar values observed in this study. In addition, several of the crucial factors cannot be fully evaluated for several years.

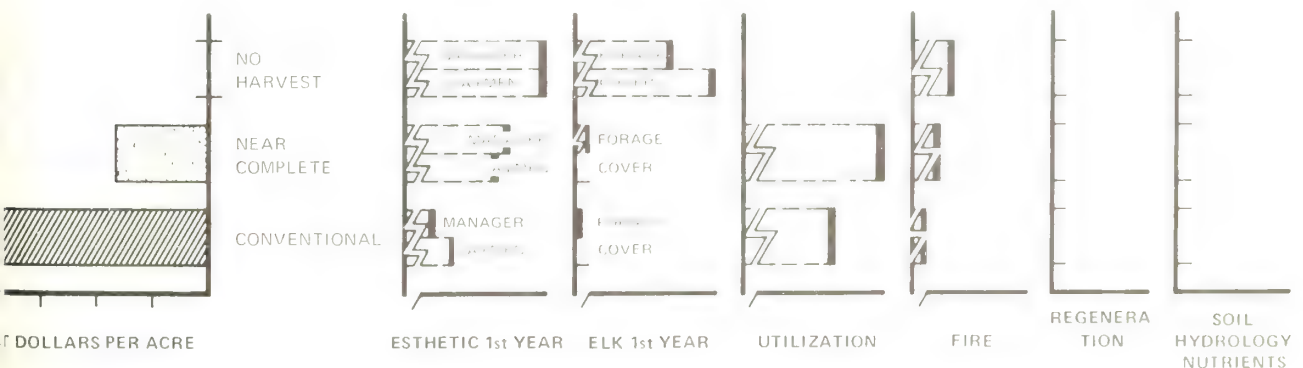


Figure 13.--Dollar and nondollar values for different logging alternatives compared with conventional logging.

The study does, however, provide a method for comparing conventional and near-complete logging over much of the mature lodgepole pine forests of the Mountain States and Canada.

The following are principal findings of the study:

1. It is technically feasible to chip most of the logging residues at the logging site; the chips are suitable for manufacturing wood products such as particleboard.
2. Dollar cost of converting residues to chips in the field was greater than dollar returns for chips alone, even if higher chip values are assumed and more efficient logging operations were attained. This illustrates the importance of recovering merchantable sawlogs, even where residues are chipped.
3. Net dollar value of conventional logging is greater than that of near-complete logging over the whole range of assumptions and alternatives analyzed, but the difference diminishes as logging and regeneration conditions improve.
4. In the set of conditions chosen for analysis as a practical and attainable operation the near-complete logging returned \$262 per acre less than conventional logging. This means that any nondollar values gained in the near-complete logging would have an opportunity cost of \$262 per acre. If chip values are \$14.50 per bone dry unit, however, the two methods have equal dollar return.
5. The no-harvest alternative is superior to either conventional or near-complete logging in terms of esthetics and wildlife (using elk as a basis).
6. Esthetic and utilization values are higher on the near-complete areas than on the conventional areas. For fuels management and for wildlife, there is no appreciable difference between logging methods. Regeneration success and the soil-hydrology-nutrient regimen cannot be evaluated for several more years.
7. From a practical standpoint, the near future of 10 or 20 years hence should be considered the relevant time period for comparing nondollar benefits. After that, nondollar considerations on conventional and near-complete logging areas are expected to have similar value.

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APPENDIX

Table 4.--Net dollar values per acre for various logging and postlogging treatments

Conditions		Net \$/acre	
		Conventional	Near-complete Chips=\$0 Chips=\$7
Actual; pile/burn and plant	524	-443	-103
Uniform volumes with 80 percent sawlog recovery; pile/burn and plant	416	-96	-16
Uniform volumes; 100% sawlog recovery; pile/burn and plant	416	-91	114
Uniform volumes; 100 percent sawlog recovery; favorable logging; broadcast burn and plant	451	146	188
Uniform volumes; 100 percent sawlog recovery; favorable logging; broadcast burn and seed	498	288	308

Table 5.--Sawlog and chip volumes, near-complete and conventional units

Products	Near-complete			Conventional		
	Unit 1	Unit 4	Ave.	Unit 2	Unit 3	Ave.
Sawlog:						
Inventoried volume, Mbf/acre ¹	20.5	18.7	19.6	24.9	22.0	23.4
Harvested volume, Mbf/acre ²	14.7	15.2	15.0	25.1	21.4	23.2
Assumed uniform volume, Mbf/acre	--	--	20	--	--	20
Residues:						
Inventoried volume, BDU/acre ³	49.6	48.5	49.0	--	--	--
Harvested volume, BDU/acre ⁴	50.1	45.4	47.7	--	--	--
Assumed uniform volume BDU/acre						
80 percent sawlog recovery	--	--	40	--	--	--
100 percent sawlog recovery	--	--	35	--	--	--

¹Converted from inventory cubic volumes reported in footnote 2 below.

²R. B. Gardner and David Hann. Utilization of lodgepole pine logging residues in Wyoming increases fiber yield. USDA For. Serv. Res. Note INT-160, 1972.

³Sum of nonsawlog trees, top portions of sawlog trees, and material on ground, converted from cubic volumes in footnote 2 above.

⁴R. B. Gardner and W. S. Hartsog. Logging equipment, methods, and cost for near-complete harvesting of lodgepole pine in Wyoming. USDA For. Serv. Res. Pap. INT-147, 1973.

Table 6.--Logging costs, stump to truck

Products	Near-complete	Conventional
- - - Dollars per unit ¹ - - -		
Sawlogs, Mbf:		
Actual	23.07	22.83
Simulated favorable logging	17.70	--
Chips, bone dry unit:		
Actual	14.93	--
Simulated favorable logging	11.33	--

¹Derived from Gardner and Hartsog, Logging equipment, methods, and cost for near-complete harvesting of lodgepole pine in Wyoming. USDA For. Serv. Res. Pap. INT-147, 1973.

Table 7.--Wildlife evaluation for various

(Index: 0 = least favorable for species; 100 = most favorable for species)

			Year 1		Year 20		Year 100	
			Forage	Cover	Forage	Cover	Forage	Cover
MOOSE								
Uncut Stand			90	100	80	100	70	100
Near-complete	Natural regeneration		10	0	50	30	90	100
do.	Planted		10	0	50	70	90	100
Near-complete								
chip spread	Natural regeneration		0	0	10	10	30	40
do.	Planted		0	0	10	70	70	100
Pile/burn	Natural regeneration		5	5	50	50	90	100
do.			5	5	50	70	90	100
B'dcast burn	Natural regeneration		5	5	50	50	90	100
do.	Planted		5	5	50	70	90	100
ELK								
Uncut Stand			70	100	60	100	50	100
Near-complete	Natural regeneration		10	0	100	50	90	100
do.	Planted		0	0	100	70	90	100
Near-complete								
chip spread	Natural regeneration		0	0	20	10	40	50
do.	Planted		0	0	20	70	40	100
Pile/burn	Natural regeneration		5	0	100	50	90	100
do.	Planted		5	0	100	70	90	100
B'dcast burn	Natural regeneration		5	0	100	50	90	100
do.	Planted		5	0	100	70	90	100
BIRDS								
Near-complete	Natural regeneration		10	0	50	70	90	100
do.	Planted		10	0	50	80	80	90
Near-complete								
chip spread	Natural regeneration		0	0	10	70	50	70
do.	Planted		0	0	10	80	50	90
Pile/burn	Natural regeneration		10	30	80	70	90	100
do.	Planted		10	30	80	80	90	90
B'dcast burn	Natural regeneration		10	30	80	70	90	100
do.	Planted		10	30	90	80	90	90
POCKER GOPHERS								
Uncut Stand			30		30		10	
Near-complete	Natural regeneration		10		100		60	
do.	Planted		10		80		10	
Near-complete								
chip spread	Natural regeneration		0		10		20	
do.	Planted		0		5		10	
Pile/burn	Natural regeneration		10		100		30	
do.	Planted		10		80		30	
B'dcast burn	Natural regeneration		10		100		60	
do.	Planted		10		80		5	

Source: G. Gruell, Office Report, Teton National Forest, June 15, 1973

Table 8.--*Manager's esthetic evaluation for alternative harvest method first year after logging and projections for 10 and 20 years hence*

(Index number, 0 = low esthetic value, 100 = high esthetic value)

Activity viewpoint	: :	No harvest	: :	Conventional: pile/burn	: :	Near- complete	: :	Chips spread
FIRST YEAR								
Moving car		100		20		73		67
Hiking or horseback		100		10		71		65
Camping		100		15		73		67
Picture taking		100		10		71		65
From overlook		100		5		68		62
From aircraft		100		20		73		67
Recreation day use		100		5		71		65
YEAR 10								
Moving car		94		30		88		69
Hiking or horseback		88		20		83		67
Camping		90		25		88		69
Picture taking		85		20		83		67
From overlook		80		15		78		64
From aircraft		95		30		88		69
Recreation day use		80		15		78		67
YEAR 20								
Moving car		77		45		100		71
Hiking or horseback		70		35		100		69
Camping		72		40		100		71
Picture taking		70		35		100		69
From overlook		68		30		100		66
From aircraft		77		45		100		71
Recreation day use		68		30		100		69

Source: Derived from office report, Wyoming Logging Residue Study--Esthetic and Recreation Evaluation, by Reed Stalder, USDA Forest Service, Regional Office, Ogden.

BENSON, ROBERT E.

1974. Lodgepole pine logging residues: management alternatives. USDA For. Serv. Res. Pap. INT-160, 28 p., illus. (Intermountain Forest & Range Exp. Station, Ogden, Utah 84401.)

Dollar and nondollar values are compared for alternative residue utilization levels in mature lodgepole pine.

OXFORD: 31; 33. KEYWORDS: timber operations, slash, logging residue, utility values, lodgepole pine.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

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Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with University of Montana)

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